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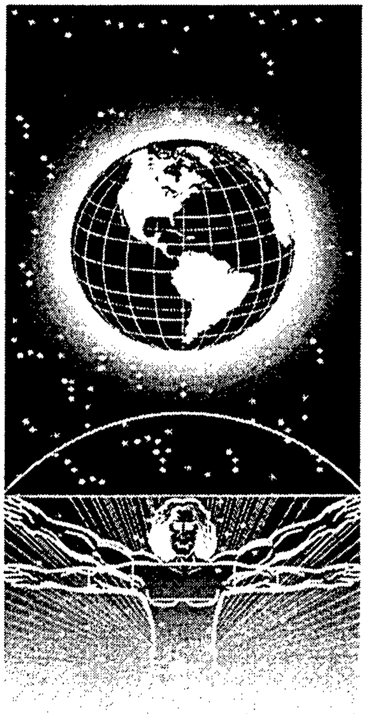

UNITED STATES AIR FORCE RESEARCH LABORATORY

3D GRAPHICS INVESTIGATION

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FOR THE COMMANDER

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13. ABSTRACT *(Maximum 200 words)*
The purpose of this study was to test three dimensional (3D) technology as a means of facilitating the presentation and interpretation of graphical information used to support complex maintenance tasks. The focus of the study was on graphic performance (user or software) and human factors issues. To accomplish this study, the team conducted a cognitive task analysis (CTA) to determine how aircraft maintainers could use 3D graphics. The results of the CTA were used to formulate requirements for candidate 3D file formats and viewers. The team then identified and evaluated 3D file formats and viewers to determine two "best-value" 3D file and viewer candidates. Finally, a comparative study was conducted with aircraft maintainers to gather data on the features and usability of the two "best-value" 3D file and viewer candidates.

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PREFACE

This technical report contains the finding of the 3D Graphics Investigation Study project. This project is Delivery Order 16 of the Logistics Technology Research Support (LTRS) program (Contract F41624-97-D-5002). The work described in this report was performed during the period 18 December 1997 through 18 August 1998. The principal investigators for this effort were lstLt. Maurice Azar from AFRL/HESR, Capt. Mike Clark from AFRL/HESR, Nicholas Stute from TASC, Inc., Holly Bautsch and Matthew Gdowski from Logicon Technical Services, Inc.

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ACRONYMS

ABDAR	Aircraft Battle Damage Assessment and Repair
ABDR	Aircraft Battle Damage Repair
AFSC	Air Force Specialty Code
AMCLDs	Active Matrix Liquid Crystal Displays
APG	Auxiliary Power Generator
CAD	Computer Aided Design
CC3D	Community Client 3D
CLSS	Combat Logistics Support Squadron
CRT	Cathode Ray Tube
CTA	Cognitive Task Analysis
DCM	Deputy Commander for Maintenance
DEPTH	Design Evaluation for Personnel, Training, and Human Factors
DoD	Department of Defense
DWB	Designer's Workbench
DXF	Drawing Interchange Format
FLT	OpenFlight
FOD	Foreign Object Damage
GFOV	Geometric Field-of-View
GUI	Graphical User Interface
HTML	Hypertext Markup Language
HLR	Hidden Line Removal
IGES	Initial Graphics Exchange Specification
JEIM	Jet Engine Intermediate Maintenance
LCD	Liquid Crystal Display
LOD	Level Of Detail
LRU	Line Replaceable Unit
NFF/ENFF	Neutral File Format/Extended Neutral File Format
OBJ	Wavefront
POV	POV-Ray
QRL	Quick Reference Lists
SEDRIS	Synthetic Environment Data Representation & Interchange Specification
SGI	Silicon Graphics, Inc.
SME	Subject Matter Expert
SPD	Standard Procedural Database
SSN	System Subject Number
STE	Space Time Editor
3DS	3D Studio
TOs	Technical Orders

ACRONYMS (Continued)

URL	Universal Resource Locator
UXO	Unexploded Ordnance
USAF	United States Air Force
VAG	VRML Architecture Group
VAR	Value-Added Re-seller
VR	Virtual Reality
VRML	Virtual Reality Modeling Language
WWW	World Wide Web

INTRODUCTION

Background

The current trend within the United States Air Force (USAF) is to replace the traditional paper-based aircraft maintenance Technical Orders (TOs) with electronic TOs. The USAF uses a great deal of photographs and graphics in TOs, but the graphic images are usually depicted as fixed oblique perspective views. Therefore, paper-based technical data leaves the maintainers with no recourse or option to manipulate the graphics to render a more useful perspective. Whether the problem is one of reversed perspective (inside-out image – outside-in real view), mirror imaging, or displaced orientation, paper-based TOs can only provide a finite number of views in the limited amount of space available. Maintainers may not intuitively interpret these perspectives and an alternative view may be more useful. Initial applications of electronic TOs have used two-dimensional graphics similar to those used in the paper TOs. The computer technology used to present electronic TOs provides a potential solution to the problem of fixed perspective graphics - the use of dynamic 3D graphics.

In today's world of increasingly faster computers and increasingly complex graphic engines, the old method of representing 3D objects by orthographic projection (three separate static views at 90° rotations) and isometric views has given way to perspective projections of wireframe and solid models. It has long been known that 2D representations of 3D objects are perceived as 3D objects (Shepard & Metzler, 1971), however, the question remains whether computer display-based representations (3D "models") have a significant advantage over standard printed graphics. Unlike 3D computer models, paper-based graphics are not only two-dimensional, they are further limited in their ability to represent 3D images because of the static nature of the medium. The ability of computer-based displays to represent information dynamically and allow interaction with 3D models adds a significant dimension in maximizing information transfer – 3D model images are not only subjectively preferred, but they have been found to increase performance as well (Bemis, Leeds & Winer, 1988). The application of this 3D graphic technology to electronic TOs has the potential to enhance the aircraft maintainer's efficiency and accuracy when executing routine and Aircraft Battle Damage Assessment and Repair (ABDAR) maintenance tasks.

The Logistics Readiness Branch (AFRL/HESR) of the Crew Survivability and Logistics Division (AFRL/HES) conducted this study to investigate the feasibility of using 3D graphic technology in electronic TOs. Part of HESR's mission is to perform logistics technology research and development focused on improving the performance of integrated systems of people, information, and equipment doing essential acquisition and logistics support functions in peacetime and war.

Current Study Objectives and Approach

Research and development in computer 3D graphics has resulted in the availability of several hundred 3D file formats and software tools for designing and presenting 3D graphics. The purpose of this study was to evaluate 3D graphics technologies and presentation formats for potential application in electronic TOs to support complex maintenance tasks such as evaluating structural damage to aircraft.

Three main objectives were identified for this study:

(1) Establish requirements for 3D graphics and determine how aircraft maintainers could use them to execute their job responsibilities more efficiently and accurately.

(2) Identify all 3D file formats and 3D viewers currently used by the commercial sector and the Department of Defense (DoD) and evaluate the identified 3D file formats and viewers to determine the two "best value" file formats and viewers for maintenance applications.

(3) Conduct a comparative study of the two "best value" viewers using a realistic maintenance scenario to gather data about the effectiveness, usability, and limitations of the "best value" file formats and viewers for maintenance tasks.

The first phase of the study focused on performing a literature review and conducting a Cognitive Task Analysis (CTA). The literature review concentrated on human factors issues such as user perception and interpretation of 3D graphics, human factors aspects of the graphical user

interface (GUI), display thresholds and limitations, interactive control of 3D objects, screen attributes, and the use of color. The results of the literature review can be found in the section titled "Literature Review of 3D Graphics Human Factor Issues".

The purpose of the CTA was to gather information from aircraft maintainers on their views about potential uses of 3D graphics in a maintenance environment. Background information, including the benefits of CTA, is available in the section titled "Cognitive Task Analysis Background". A description of the CTA conducted for this study and its results are given in the section titled "Cognitive Task Analysis".

The second phase of the study concentrated on identifying industry standard 3D file formats and viewers. The study targeted both commercially available and DoD standard formats and viewers. The scope of this effort was to look exclusively at existing file formats and 3D viewers and not to develop custom software. After identifying all available formats, the team evaluated and ranked each of the file formats and viewers. The first step in the process involved developing a set of evaluation criteria for both the file formats and viewers. Once the criteria were outlined, each of the file formats and viewers were reviewed and ranked. Based on the results of the ranking, two file formats and two viewers were recommended as "best value" for this effort. The sections titled "3D File Formats" and "3D Viewers" contain the details of this phase of the study.

The third and final phase of the effort was to conduct a comparative study of the two identified viewers using aircraft maintainers from the 653 Combat Logistics Support Squadron at Robins AFB, GA. The first step consisted of building a 3D computer model of Avionics Bay 3R of the USAF F-15 aircraft. Details of this process are given in the section titled "3D MODEL CREATION PROCESS." The maintainers at Robins AFB were then asked to perform a simulated maintenance task involving Avionics Bay 3R. This phase of the project was designed to integrate the information obtained from the literature review, CTA, and format evaluations by providing the maintainers the opportunity to interact with the 3D F-15 model of the avionics bay. By using the identified viewers, maintainers could evaluate the use of 3D models for maintenance tasks in general and the effectiveness of these two "best value" viewers in

particular. Extensive data from the maintainers was gathered during the study. Details and results of the study are given in the section titled "COMPARATIVE STUDY."

This report concludes with a summary and discussion of directions for further research.

BACKGROUND FOR EVALUATION OF 3D GRAPHICS

Literature Review of 3D Graphics Human Factor Issues

Interpretation and Perception of 3D Graphics on 2D Displays

A review of current literature was performed to determine the usefulness of 3D graphic imagery given the limitation of using a standard 2D display. This literature is reviewed below. Some aspects of the review may not be directly applicable to the CTA, file format evaluation, and comparative study phases of the current project, but are mentioned for completeness and future reference.

While "true" binocular 3D stereo displays are available (i.e., displays that use disparity information to present objects that appear to float in space), they are expensive and usually require special glasses or expensive hardware. Therefore, standard LCD or CRT monitor displays are preferred for general applications such as most maintenance tasks.

It has been shown that the use of graphics and visual models can significantly increase the speed and accuracy of information transfer, especially when the properties and limitations of visual perception are taken into account (Haber & Wilkinson, 1982). Three-dimensional surface models can increase a user's ability to discern information by adding global information that may not be obvious from 2D orthographic projections and also by shifting some of the user's cognitive load to the perceptual system (Robertson, Mackinlay & Card, 1991). Furthermore, 3D models can add this global information without masking individual part identity (Pomerantz, 1986).

One concern about the use of 3D graphics is that users may have different levels of ability for spatial reasoning that may affect their ability to use and understand 3D graphics. While this may be true for some new users, it has been shown that through learning and practice, this ability can be improved (McCuistion, 1991; Osborn & Agogino, 1992; Wiley, 1990; Wiebe, 1991).

Monocular Depth Cues. A primary attribute for perceiving depth is stereopsis, wherein the two eyes receive slightly different views of an object and the disparity of edges and textures gives a clue to their location in depth. However, even without binocular stereo information, there are many other monocular cues to depth, including size, linear perspective, occlusion, motion parallax, texture gradients, shadowing, contrast, clarity, and brightness (see Wickens, Todd & Seidler, 1989; Majchrzak et al., 1987, pg. 132-136). Texture, contrast, clarity, and brightness tend to add little to depth perception while requiring large computational costs. Furthermore, because of possible ambiguities in perception, size and shadowing effects can actually cause misinterpretations of depth. Therefore, the most salient monocular depth cues are motion, perspective, and occlusion. These alone have been shown to overcome a lack of stereopsis to give powerful cues to three-dimensionality (Wickens, Todd & Seidler, 1989; Zhai, Buxton & Milgram, 1996).

Motion is especially useful, as it can be used to unambiguate 2D projections of 3D forms by using object displacement to give information about surface segmentation (Kaiser & Proffitt, 1989). It also allows the perceptual system to track parts of objects and relationships between these parts because of object constancy, and the user can keep these relationships assimilated even after the object stops moving (Robertson, Mackinlay & Card, 1991). Furthermore, while motion can aid in the initial identification of objects and object parts, further manipulation of that object's orientation does not deleteriously affect the identification of that object (Biederman & Gerhardstein, 1993). In addition, see Jolicoeur, 1992, who cites studies that show that rotation of objects with a standard orientation, like faces or text, etc., does reduce performance. The ability to actively manipulate 3D object models on 2D displays provides for faster, more accurate object identification than when limited to static graphics (however, it should be noted that for abstract data visualization — as opposed to concrete object perception — motion gives no significant performance benefits over static 3D perspective representations (Wickens, Merwin & Lin, 1994)).

Geometric Modeling — Wireframes, Solid Models, and Shading. There is little consensus on the precise terminology used for geometric models. However, for purposes of

clarity, we will consolidate the images used in the reviewed studies into four basic model types: wireframes, line drawings, surface models, and solid models.

Straight *wireframe* models simply use thin interconnected lines to represent the edges of the object and appear as see-through outlines of the objects. Wireframes have disadvantages because they do not show the surfaces of the objects and ambiguous representations can occur (Groover, 1992). Use of dashed lines or semi-transparency (reduced contrast) for lines that would be obscured in real objects helps reduce but not eliminate ambiguity (Zhai, Buxton & Milgram, 1996). *Line drawings* are wireframes that use hidden line removal (HLR), or the removal of lines that would be obscured by other portions of the real object. Line drawings also help to alleviate some of the ambiguity of wireframes but still lack shading and texture elements and poorly represent smooth curvature of surfaces. *Surface models* have shading, texture, and shadowing, but are still represented as wireframes or polygonal surfaces in the computer. Finally, *solid models* are constructed and represented as solid 3D shapes in the computer and have mass and density properties consistent with the object materials (Groover, 1992). Many visual studies use the term "solid model" when they are really referring to a surface model. There are definite benefits of solid models for CAD/CAE/CAM applications (e.g., the ability to calculate weight and center-of-gravity of objects and groups of objects), however, these benefits are not necessary when 3D object models are simply being used for visualization.

The advantages and disadvantages of wireframe, line drawings, and surface models is in terms of their ease of relating depth and their perceived realism. While complex, full color, shaded renderings provide the most true-to-life representation of objects, simple line drawings of the same objects, although appearing less realistic, can be identified as quickly and accurately (Biederman & Ju, 1988). The question becomes how much and what type of information should be included in renderings of 3D objects to yield good performance and realism without resulting in overkill.

Subjective ratings of perceived realism and the amount of geometric information conveyed have shown that wireframe, line drawings, and shaded surface models all adequately convey information about geometric content, but shaded surface models are judged to be the most realistic (McWhorter, Hodges & Rodriguez, 1991). Mental rotation tasks (in which subjects

are asked whether two views of a 3D object are of the same or different objects) also show that shaded surface models give significantly better results (in terms of reaction times and error rates) than wireframe or line drawings (Barfield, Sandford & Foley, 1988). This study also found that the addition of a second source to the lighting model significantly improved perceived realism while manipulations in the type of shading had no effect. This indicates that computing power may be better spent on lighting cues than on shading.

Human Factors Aspects of the Graphic User Interface

Many aspects of the GUI are relevant to the display and manipulation of 3D images and merit brief mention. These include the effective field-of-view of the graphic window, user manipulation of 3D objects using conventional controls, and screen attributes such as screen design and clutter. A final aspect, the use of color, will be dealt with to a greater degree due to its complex perceptual nature.

Geometric Field-of-View. The geometric field-of-view (GFOV), sometimes called the scene field-of-view, is defined as the field-of-view of the computer's eye for the viewport of the graphics (Barfield, Lim & Rosenberg, 1990). This may or may not (and usually does not) coincide with the user's field-of-view in terms of the angular aspect of the display monitor at the user's viewing distance. For most applications that display simple objects, the question of GFOV is not relevant; however, certain 3D images that relate to large-scale relationships of objects on real-world assemblies, such as images of large portions of a wing section or other aircraft assemblies, may benefit from optimal GFOV parameters. No study has looked at these parameters for 3D object displays *per se*, but in studies of other applied spatial tasks, it has been found that the optimal GFOV for accuracy of directional judgments is that which matches the display FOV at the user's eye (Barfield, Lim & Rosenberg, 1990; McGreevy & Ellis, 1986) and has an eye-point elevation of between 15° and 45° (Hendrix & Barfield, 1997).

Interactive Control of 3D Objects. The presentation of 3D objects on 2D displays also leads to questions of how users will interact with those objects. To gain the full benefit of 3D object modeling, objects need to be manipulated in different ways such as translation, rotation about any axis, and size scaling. Translation would be useful to shift parts vertically or

horizontally to avoid occlusion and rotation would provide views of previously-hidden object surfaces. The need for a zooming (or size scaling) control is due to the limited resolution and screen size of the display. Certain aspects of a perspective drawing may need to be magnified or "exploded" to visualize individual parts, wires, or connections.

While detailed descriptions are beyond the scope of this report, it should be noted that conventional controls (such as a mouse or trackball) have been found to provide adequate control when used with appropriately-designed software "virtual" controls such as slider controllers or more specialized designs (Chen, Mountford & Sellen, 1988; Houde, 1992) or even allow for different types of task-dependent virtual controllers (Nielson & Olsen, 1986).

Screen Attributes. Another relevant aspect of graphic display is screen design (see Liu, 1997, for a review). Proper use of indentation, grouping, and size help reduce clutter and make screens easier to read. Color, highlighting, and blinking can reduce search time for finding relevant items. Borders around display areas have been found to aid in separating elements and reducing the effects of clutter (Matin & Boff, 1988). Furthermore, proper layout of the GUI into well-defined sections with minimal text and data can aid in user manipulation and understanding of spatial images (Osborn & Agogino, 1992).

Environmental Effects on Color Active-Matrix Liquid Crystal Displays. A user's ability to discriminate and identify a display's graphic image is a function of the environment in which the display is viewed. An important environmental factor is ambient illumination, which reduces a display's luminance and chromatic contrast and produces a visual adapting luminance for the user. Lower luminance contrast makes differentiation of image detail more difficult. In addition, lower chromatic contrast results in chromatic gamut reduction or "washout" (the "purest" colors are less saturated due to mixing with ambient light, so fewer colors can be produced).

Most notebook and wearable computers incorporate active matrix liquid crystal displays (AMLCDs). These displays are well suited for use in high ambient illumination environments; since they reflect less than 1% of incident ambient illumination, they are also suitable for use in maintenance environments. Krantz, Silverstein, and Yeh (1992) investigated the effects of ambient illumination and adapting luminance on an AMLCD for a spatial discrimination task.

The study found ambient illumination up to ~100,000 lux (the same as that produced on a horizontal plane by the sun at 50° above the horizon on a clear day) and adapting luminances up to ~30,000 cd/m^2 (equivalent to a light colored object under direct sunlight) had no effect on the task when display luminance was at least 180 cd/m^2 (a typical laptop LCD can produce a luminance of ~100 cd/m^2). However, spatial discriminations for displays producing less than 180 cd/m^2 were most affected by the adapting luminance, in particular, when adapting luminance exceeded display luminance by a ratio of more than 100:1. Chromatic gamut reduction for AMLCDs, or the inability to produce pure colors due to desaturation from ambient illumination, varies from nearly zero at ~10,000 lux ambient illumination (similar to that produced on a horizontal plane by white clouds at mid-day) to about 40% at ~100,000 lux. Therefore, to assure maximum legibility, users should orient their display to minimize incident light, ambient illumination, and adapting luminance.

Finally, it should be noted that some characteristics of AMLCD hardware may be responsible for use limitations during certain maintenance tasks. While AMLCDs compare favorably with most other display technologies (plasma, vacuum fluorescent, and electroluminescent) in terms of display attributes such as pixel density, screen resolution, and contrast, AMLCDs can satisfactorily operate only across a relatively narrow temperature range (MacDonald & Lowe, 1997). The U.S. Congress Office of Technology Assessment (1995) reports that, "low temperatures affect LCDs primarily in two ways: 1) a reduction in response time and color gamut shift necessitates the need for heaters and programmable look-up tables, and 2) the backlight required for an LCD-based display must incorporate heaters in order to turn on at cold temperatures. In addition, liquid crystal materials and polarizers often suffer irreversible damage at temperatures above 90°C."

Color in Information Display. Color is an important dimension of graphics visualization. Advantages of using color include the ability to convey realism, designate or emphasize, segment, warn/signify, group, imply states, and improve aesthetics (Galitz, 1997; Heath & Flavell, 1985; Travis, 1991). For example, in a medical application, three-dimensional images were more easily interpreted when the various transparent overlapping elements were colorized

(Brown, Earnshaw, Jern & Vince, 1995). Also, Wiebe (1991) found that long-term study of complex spatial relationships and visualization of global form were enhanced by using color. However, if used improperly, color introduces problems such as distractions, perceptual phenomena which vary according to viewing and stimulus conditions, errors or ambiguities for color anomalous (or "color blind") observers, information overload, and conflicting cultural and/or historical messages (Brown *et al.*, 1995; Horton, 1991; Galitz, 1997).

Many principles and guidelines exist for designing color into information displays. Travis (1991) suggests two general design principles. First, design the interface for a monochrome display. Color should be a redundant coding dimension and used only in cases where there is a clear requirement. Second, colors should be consistent with the user's mental model. Color coding "systems" will be effective only when the colors match what the user expects to see (the colors are appropriate for the given context).

Several reports address color design guidelines such as recommended applications, combinations to avoid, and size and orientation constraints (Murch, 1987; Post, 1997; Travis, 1991). Large hue differences should be used for qualitative information (to delineate categories) while luminance and saturation differences (or small hue differences) are preferable for representing quantitative data (options or state levels) (Heath & Flavell, 1985). Color should not be used for an arbitrary ordinal scale, because color does not scale uniformly (Kaiser & Proffitt, 1989). However, for color object coding, perceptual and cognitive studies have shown that when the user must perform an absolute identification task, the number of colors differing only in hue should not exceed eleven (and should be the appropriate eleven), or confusion will result (Post, 1997; Walraven, 1992). Color discrimination varies between and within users, therefore color differences must be large enough to ensure that most users can differentiate them. Color discrimination and luminance contrast decreases with increasing peripheral eccentricity, requiring larger and higher contrast, respectively, for peripherally presented visual information.

Three-dimensional effects in computer-aided design (CAD) and other 3D graphic applications can be improved by using blue for distinct objects and red for close objects (Brown *et al.*, 1995). Intermediate distances are represented by intermediate hues such as green, yellow, and orange. A table of the best and worst foreground/background color combinations for text and

panels, assessed via subjective preference and consistent with color phenomena discussed below, can be found in Brown *et al.* (1995). Finally, highly saturated colors can cause visual fatigue as well as induce many of the color artifacts described below.

An additional color design consideration is that color coding may be inappropriate for nearly 10% of the population (mostly male) who are color anomalous (commonly called "color blind"). Most color deficient observers confuse red, yellow, orange, and green, although a very small percentage confuse blue, cyan, yellow and white (Post, 1997). Adapting color display information for color anomalous observers requires additional design guidelines (Walraven, 1992). First, color confusion is most problematic when there is no perceived chromaticity or luminance difference. Higher luminance contrast, which takes into account a defective observer's lower luminance capability for colors associated with the defective system, can help differentiate objects. Second, color objects subtending small visual angles are more difficult to discriminate and should be avoided, especially when desaturated and/or of low luminance. Large areas, however, may be discriminated relatively well. Third, red/green defectives rely more on blue and yellow discriminations, so these colors should be included in the design. Finally, the existence of color defectives emphasizes the fact that color should be a redundant coding dimension (used in combination with luminance, shape, size, etc.) and not the only means of identification.

Inappropriate color usage in information displays can lead to numerous undesired visual phenomena and artifacts (Horton, 1991; Murch, 1987; Post, 1997; Walraven, 1992). Adjacent colors can produce simultaneous color contrast (shift in perceived hue) and therefore should be separated spatially. The human lens does not focus all wavelengths exactly on the retina. Blues focus slightly in front of the retina and reds focus slightly behind the retina (chromatic aberration), so that blue and red objects sometimes appear blurry. Simultaneous presentation of reds and blues may cause them to appear in different depth planes (chromostereopsis). Chromatic aberration and chromostereopsis increase with increasing saturation. Equally bright colors may not be distinguishable, so redundant luminance coding is often necessary. Intense or large color areas may produce color aftereffects (McCullough effect). Finally, the hue appears to shift with increasing or decreasing luminance (Bezold-Brucke effect).

In summary, color may enhance 3D model visualization for maintenance tasks, although it should be used cautiously and in accordance with the aforementioned guidelines, recommendations, and caveats. For the maintenance task under study, color will be most beneficial to help differentiate objects. The use of color as an absolute identifier (trying to reproduce the exact color of real color-coded wires) is not recommended, since color fidelity is a function of the environment, display system, and the user's visual system. The use of highly saturated colors should be minimized, but this may ultimately be determined by the degree of realism required. Finally, the design should take into account possible color desaturation and contrast reduction effects due to ambient illumination, the existence of color anomalous users, and potential visual artifacts.

3D Graphics for Maintenance Tasks

Few studies have been conducted on the applicability of 3D graphics directly to maintenance tasks. There is at least one instance in the general literature of placing computerized manuals, wiring diagrams and documentation on laptop computers for use by maintenance workers (Rankin, Allen, Sargent & Graeber, 1997); however, little is known about the efficacy of this approach. An attempt was made in this literature review to analyze the use of 3D graphics as a general means of relaying information to the viewer. In this, it was shown that 3D graphics are a powerful tool for quickly and accurately identifying parts, objects, and assemblies of objects and, therefore, should prove useful when integrated into systems to be used by maintenance technicians.

Cognitive Task Analysis Background

Review of Current Literature and Techniques

Cognitive Task Analysis is most often associated with several knowledge elicitation techniques such as knowledge acquisition with question probes and conceptual graph structures ("concept mapping"), observations, interviews, task analysis, protocol analysis, and structural analysis. CTA is actually an extension of task analysis, where the objective is to determine the cognitive abilities necessary to perform a task. Traditional task analysis accesses only the

physical, generally observable, aspects of a task, whereas CTA quantifies or represents the underlying cognitive processes that are not directly observable, thus providing an indication of cognitive workload, information processing, and decision making associated with a task.

The knowledge elicitation techniques that comprise a CTA are not applied in any set order, but rather vary with the application. CTA's flexibility is reflected in its definition, which often varies among experts. One common definition states that CTA is a knowledge acquisition procedure that involves identifying the knowledge and the cognitive skills required to perform a task at acceptably high levels (Gordon, Schmierer, & Gill, 1993). Thus, according to this definition, CTA is used to identify and solve cognitive issues that occur while performing a task. Relatively few boundaries exist when using CTA for tasks involving cognitive elements.

Three approaches have been recommended for the majority of CTA applications (Gordon & Gill, 1994). The first approach relies on a formal analysis of the application to uncover the cognitive demands of the task for a specific environment (assessing the tasks involved). A second approach relies on empirical techniques to analyze how humans perform a task (assessing the procedure). The empirical approach is particularly suitable for developing training requirements for existing systems. The third approach relies on a computer model that simulates the cognitive activities involved in completing a task (modeling the tasks and procedure). Applications of CTA often involve a mixture of all three methods (Roth and Mumaw, 1995).

Benefits of CTA

Concept mapping and semi-structured interviews were the two main techniques used to formulate the CTA. Concept mapping involves using a graphical structure to display and organize the gleaned knowledge and relationships. Semi-structured interviews use question and answer dialogs to obtain and qualify information (the section titled "COGNITIVE TASK ANALYSIS" contains more information on defining and applying concept maps and semi-structured interviews). These two specific knowledge elicitation techniques have several advantages, particularly when applied concurrently within a session.

There are several advantages in using graphical structures via concept maps to represent the process of knowledge acquisition (Gordon & Gill, 1992). The graphical structure is depicted

on a whiteboard in front of all interview participants. Thus, potential ambiguities in interpreting knowledge concepts and their relationships are minimized. This allows the subject matter expert (SME) and the analyst to easily identify missing, inconsistent, or redundant information. Flexibility in the content and type of probing questions allows the analyst to structure the interview in real-time, as needed - an essential element of a concept map. Most importantly, the probes allow the analyst, rather than the SME, to structure the interview. This is critical when attempting to gather a large body of knowledge, since the SME can easily traverse topics tangentially, leading to excessive data that may be irrelevant to the topic of interest. Additionally, SMEs report that concept map interviews are interesting, which can lead to more complete knowledge elicitation.

Verbal interviewing is one of the most common knowledge elicitation techniques (Brenner, Brown & Canter, 1985). These interviews typically focus on the SME's recall of an event or past experience via responses to verbal questions. These sessions are usually in written (notes), audio, and/or video formats, since the amount of information precludes one person from capturing it all. The audio and video tapes allow the analyst the opportunity to later review and verify key points that may have been missed in the notes.

Meister (1985) cites three common types of verbal interviews: 1) unstructured, where the SME expounds on a topic relatively unguided by the analyst, 2) semi-structured, where the SME expounds on a series of carefully-selected questions, and 3) structured, where the SME responds, usually by a forced choice, to very precise questions. Semi-structured interviews were employed in this study because the relative freedom of the SME's answers would help to uncover topics relevant to the project, but previously unknown to the analysts.

COGNITIVE TASK ANALYSIS

Method

Five F-15 and one C-141 aircraft maintainers from the 653 Combat Logistics Support Squadron (CLSS) served as the SMEs. The F-15 aircraft served as the focus because of its complicated, compact system that represents most of the difficulties encountered in aircraft when working with TO graphics. The SMEs were chosen to help identify representative tasks in which TO graphics play vital roles and to evaluate potential 3D models.

For this study, the empirical CTA approach was used. The CTA was implemented using two knowledge elicitation techniques: concept mapping and semi-structured interviews. Concept mapping was chosen because of its unique ability to capture knowledge; that is, it involves a graphical, interactive interview that involves SMEs in the elicitation process. The semi-structured interview provided an additional and more in-depth method for capturing SME knowledge through a series of probing questions.

The 653 CLSS maintains a depot of Aircraft Battle Damage Repair (ABDR) C-130, C-141, and F-15 aircraft. Their primary mission as a highly trained, dedicated, flexible, and mission-ready logistics team is to support Air Force ABDR operations. Maintainers are trained in three areas: ABDR, major maintenance augmentation (routine repair), and deployable Jet Engine Intermediate Maintenance (JEIM). Six maintainers skilled in ABDR and routine maintenance participated in the CTA study.

Knowledge Elicitation Techniques

The methodology used to collect data was developed specifically for this study. The techniques included informal briefings, questionnaires, and concept mapping and semi-structured interviews.

Informal Briefing. The analyst informally briefed each maintainer prior to the CTA sessions. The briefing contained an overview of the CTA study and objectives. The maintainer's role as an SME dealing with TOs was also established at this time.

Questionnaire. After the briefing, each maintainer completed a background information questionnaire (Appendix A). There were separate questionnaires for routine and ABDR maintenance sessions. The purpose of the questionnaires was to gather information about the maintainer's aircraft maintenance experience by aircraft type. The maintainer's Air Force Specialty Code (AFSC), an indication of experience and rank were also recorded. The maintainer's background information provided a basis from which the research team could formulate the task and structure probes in the CTA.

Concept Mapping. Concept mapping consisted of two parts: a conceptual phase and a solution or decision phase. In the conceptualization of a task or problem, the SME's perceptions of the variables involved were collected. In the solution or decision phase, the SME's responses to the variables were recorded (McFarren, 1997). In studying both phases together, an SME's representation of the problem and the solution were recorded.

The concept mapping sessions, using a verbal protocol analysis, provided specific information on the use of TO graphics and the potential use of 3D graphics in aircraft maintenance. Verbal protocol analysis can be reported in one of two ways, either in concurrent verbal or retrospective reports. These reports claim to reflect cognitive processes. Concurrent verbal reports consist of a "talk aloud" and "think aloud" phase, where the cognitive processes are verbalized in successive states. This study used the retrospective verbal report, where a memory trace of the information required to complete a task is recorded. Retrospective information comes from memory of a completed project and may expose errors or omissions identifiable only in "hindsight" (Ericsson & Simon, 1993). The maintainers were asked to vocalize their actions as if performing a specified task.

Key points were represented as nodes, or concepts, within a particular domain. Each node was depicted by text within an oval and represented a "piece" of information collected in the elicitation process. Concepts were connected through relational links denoting the association between two concepts and depicted the sequential aspect of the task. The meaning contained in any particular concept map was primarily a function of the relations between concepts. As seen in Figure 1, the top-level nodes "Scan of Cockpit Without Removing Items," "Search Areas

Difficult to Reach," and "Search Additional Areas" represents the steps involved in the location of Foreign Object Damage (FOD) in a cockpit.

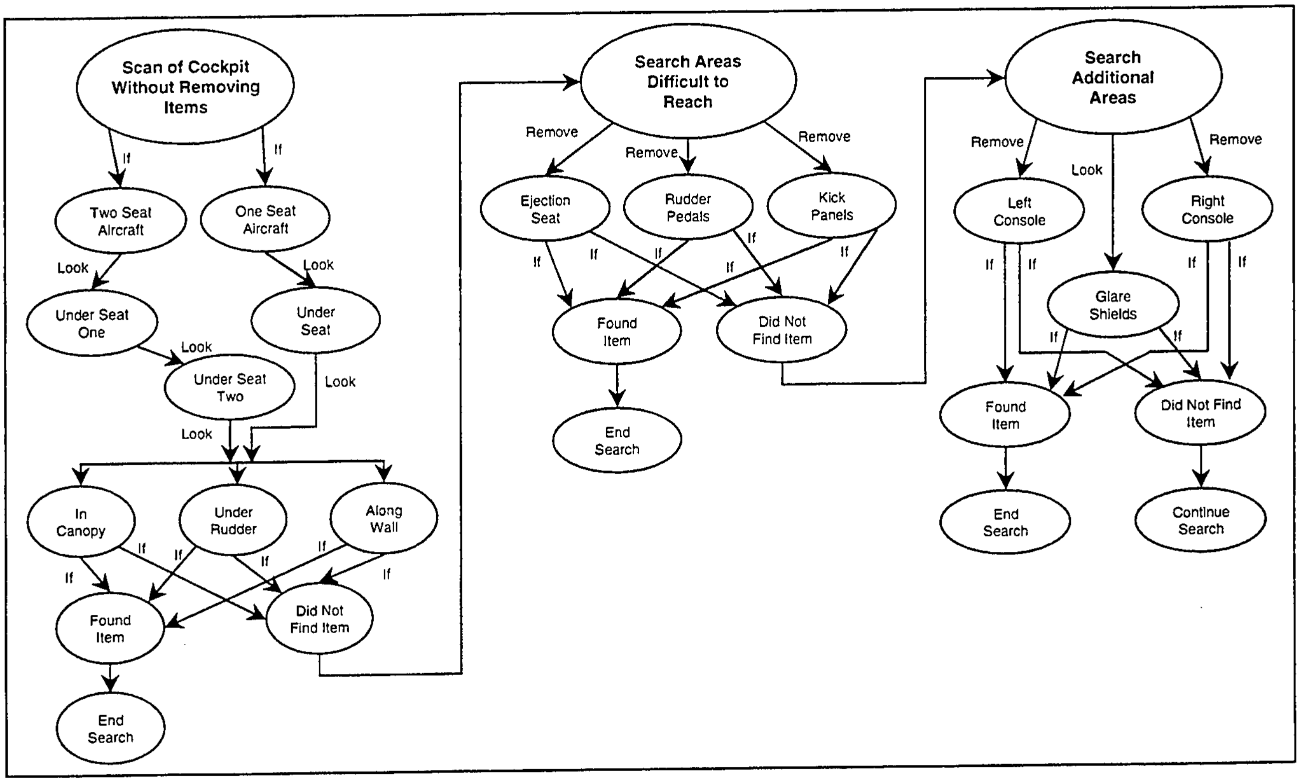


Figure 1. Representative Concept Map.

Semi-structured Interviews. As already mentioned, the content of the semi-structured interviews was predetermined and the sequence and length of responses was allowed to vary. The semi-structured interview format allowed a more complete coverage of the SME domain knowledge than may be covered through an unstructured interview (Cooke, 1994). All of the questions addressed points regarding the requirements of 3D graphics for use in routine and ABDR maintenance. These questions were developed from an in-depth literature review of maintenance activities and interviews with maintenance personal prior to the CTA.

Experimental Procedure

Each maintainer participated in two CTA sessions. One session focused on routine aircraft maintenance while the other session focused on ABDR maintenance. During the first

session, the maintainer was briefed on the study (see Informal Briefing), then given a background information questionnaire. For each session, concept mapping interviews were conducted followed by the semi-structured interview. The CTA sessions each lasted 60 to 90 minutes.

A team of three researchers participated in the CTA sessions. During the concept mapping interviews, one team member served as the analyst and transcribed the map onto a large whiteboard. The two other team members, along with the analyst, guided the maintainer through a representative task by asking question probes.

In both CTA sessions, routine and ABDR, the maintainers were asked to "walk through" a pre-selected aircraft maintenance task. The scenarios for routine maintenance included:

- Foreign Object Damage
- Brake Change
- Inspection by Feel
- Perspective Problem

The scenarios for ABDR maintenance were specific to each maintainer's repair specialty. Three different specialties were encountered:

- Crew Chief
- Electrician
- Sheet Metal

Appendix B contains a detailed explanation of all seven scenarios. Once a scenario had been explained, the maintainer was asked to break the task down into three to five steps. These steps formed the top-level nodes for the concept map and the maintainer was asked to develop each concept. There were no restrictions placed on the order in which the maintainers developed the nodes. As the maintainer spoke, the analyst drew the map on a large whiteboard in front of the maintainer and the research team. As part of the inherent validity in the concept mapping procedure, the maintainer was encouraged to make changes and clarifications to the map

whenever appropriate. The session ended when the maintainer felt he had completely represented his actions during task.

After completing the concept map, the CTA transitioned to a semi-structured interview. The maintainers were asked a series of questions categorized into two groups: (1) Do the current graphics in the TOs help you perform your maintenance? and (2) Would 3D graphics aid maintenance? The goal of the interview session was to gather the maintainer's opinion of the current TO graphics and the potential use of 3D graphics. The questions were repeated for each of the maintainers. Although these questions were established before the session began, slight modifications were made to incorporate information gathered from the concept maps. The entire CTA session was audio- and video-recorded to ensure no loss of information.

Subjects

Six aircraft maintainers from the 653 CLSS, stationed at Robins AFB, Warner Robins GA, participated in the study. Skill levels ranged from 3-level to 7-level. One of the maintainers did not have maintenance experience with the F-15 aircraft, but rather had C-141 maintenance experience. All participants had routine and ABDR aircraft maintenance experience. On average, the maintainers had eight years F-15 routine maintenance and four years F-15 ABDR maintenance experience.

Data Analysis

The raw data consisted of the research team's notes, audio and video recordings of all information sheets, concept maps, and semi-structured interview sessions. Over 150 pages of transcribed data were compiled. The data set was used to clarify and complete the concept maps and to categorize 16 areas of interest (topics) identified in the semi-structured interview.

Concept Map Analysis

The concept maps provided detailed information regarding the use of current TO graphics within the context of routine and ABDR repairs. Direct observation of a maintenance task could have added validity to the concept mapping data and identified any additional difficulties encountered by the maintainer. However, observation was not possible due to time constraints.

Only a retrospective verbal report could be obtained. Two maps were created for each maintainer: one regarding routine maintenance and one regarding ABDR maintenance. The research team made special notes whenever graphics were referenced.

The information in the maps depicted the importance of and the order in which the TO graphics were referenced for a particular task. The maps will be discussed in two groups: routine and ADBR. Four unique tasks were mapped in the routine sessions (FOD, brake change, inspection by feel, and perspective problem). For the FOD scenario, graphics typically were not required to perform maintenance. A novice may, however, need to reference a graphic to become oriented in the cockpit and locate any removable items. For the brake change scenario, the TO graphics would need to be referenced to complete a tire removal. The concept map for this scenario is seen in Figure 2.

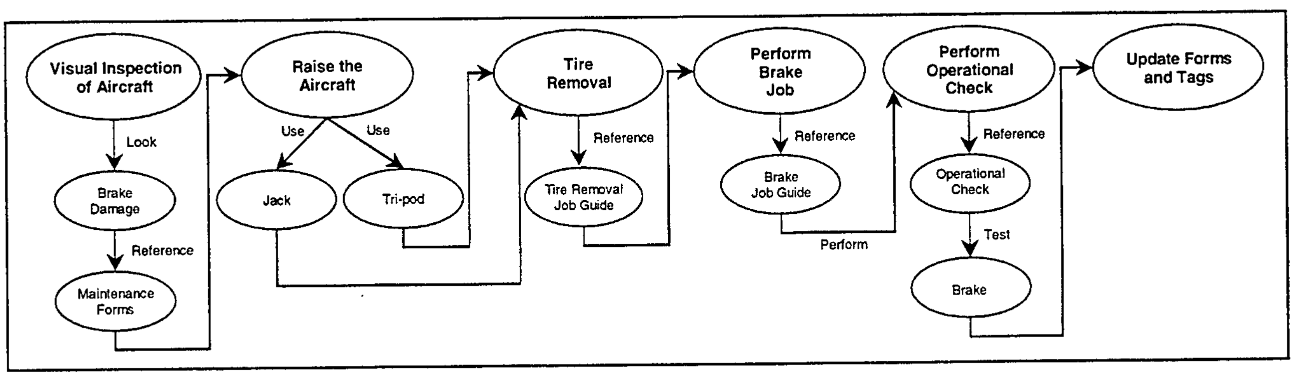


Figure 2. Brake Change Concept Map.

The inspection by feel scenario dealt with bird strikes to an aircraft. In this scenario, the graphic's perspectives were so poor that the maintainers could not determine what systems were damaged so they had to perform the inspection by feel. In the perspective problem scenario, two specific tasks were illustrated: a fire loop problem and C-141 window post replacement. For both of these tasks, a novice would need to reference TO graphics in order to locate the positions of the fire loops and window posts. In these scenarios, the TO graphics were referenced, but they were very unclear and did not aid the maintainers. Several details, such as bolts and seals, were not represented in the graphics for the fire loops and window post assembly. The C-141 window post replacement scenario is shown in Figure 3.

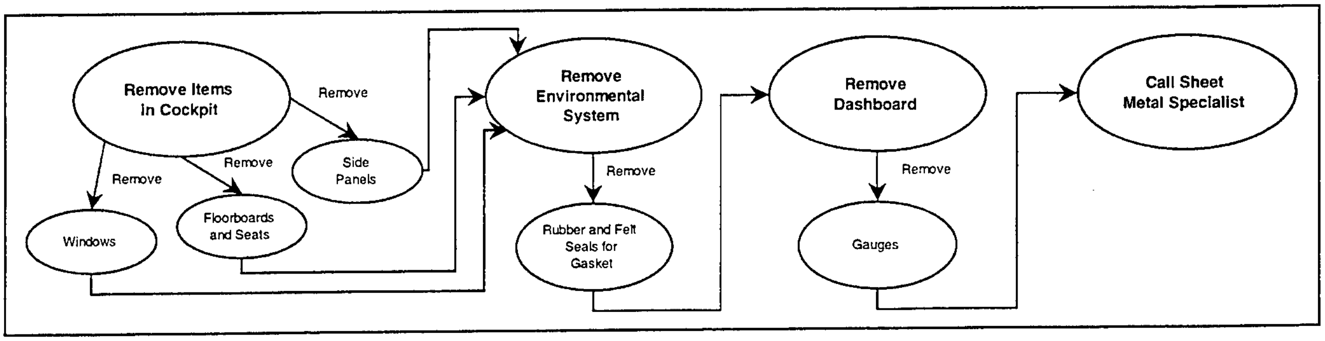


Figure 3. Window Post Replacement Map.

In the ABDR sessions four unique tasks were mapped (crew chief, electrician, and sheet metal). For the crew chief, the overwhelming trend was to use graphics to help identify damaged components and damage that may be hidden from view. Both novice and experienced maintainers use graphics at some point in their ABDR crew chief duties. Figure 4 shows a typical chew chief procedure.

In the electrical scenario the regular maintenance wiring diagram TOs were found to be more useful than ABDR TOs. For the sheet metal scenario, TOs were used to identify damage that travels through the plane. The graphics depict each layer of components to aid in maintenance. Where applicable, the maintainers rely heavily on drawings created by the engineers.

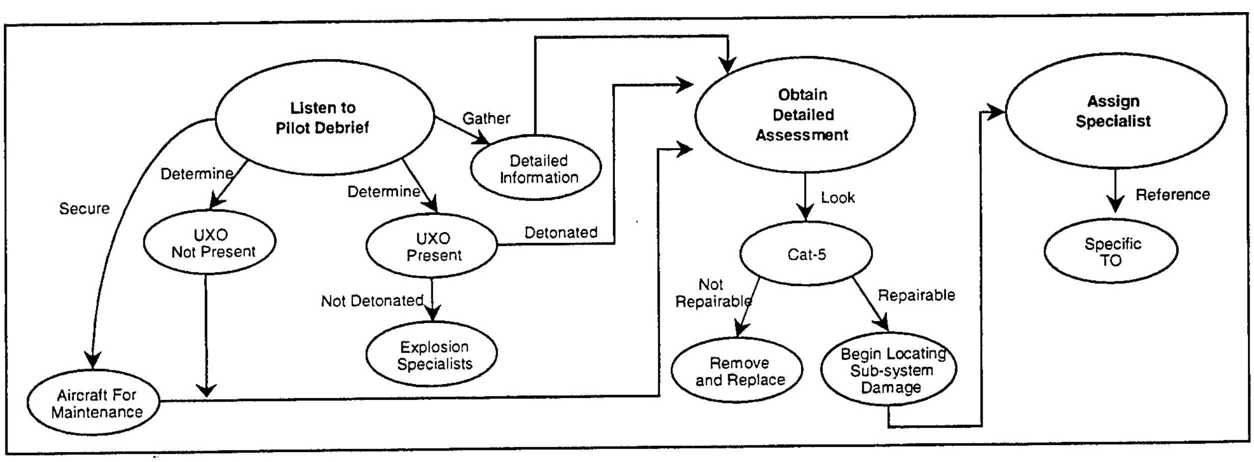


Figure 4. Crew Chief Procedure Concept Map.

Appendix C contains all six of the maintainers' concept maps for both the routine and ABDR sessions. Some maps showed the benefits of current TO graphics while other maps showed problems.

Interview Analysis

To organize the interview data, two spreadsheets were constructed to represent the maintainer's responses to the 16 topics. One spreadsheet contained responses for routine maintenance while the other was for ABDR maintenance. The same list of topics was used for both types of maintenance. The 16 topics are listed below:

1. Do TO graphics aid in maintenance? How?
2. Is there ever a time when TO graphics do not aid in maintenance? How?
3. Are there any TO graphics that are inadequate or misleading? When?
4. Does experience ever override misleading graphics? When?
5. Are there any TO graphics improperly drawn or mislabeled? When?
6. Is there ever a time when you reference supplemental material because of poor graphics? What? When?
7. Would TO graphics aid a novice? When?
8. Is there ever a time when mental rotation of a TO graphic is required to complete a job? When?
9. Was there ever a time when you had to change your visualization of a TO graphic to complete a job? When?
10. Was there ever a time when graphics were unavailable? When?
11. Would 3D graphics aid in typical/ABDR maintenance? When?
12. Would 3D graphics aid a novice? When?
13. Which TO graphics need improvement?
14. What type of improvement is needed for the TO graphics?
15. Do you ever visualize peeling away levels of a surface? When?

16. Is full manipulation of 3D graphics required?

The results of responses to the questions will be reported separately with respect to routine and ABDR maintenance and are summarized below:

Question: Do TO graphics aid in maintenance? How?

Routine Maintenance: All of the maintainers stated that TO graphics aided in performing aircraft maintenance. Without the graphics they would have to reference another aircraft or rely on the experience of other maintainers to complete repairs. They also believed that TO corrections or block upgrades to aircraft in a graphic would more likely be recognized than in text.

ABDR Maintenance: All of the maintainers stated that the ABDR TO graphics were useful, but there was room for improvement. A few maintainers suggested improving the organization of the ABDR TO to allow for easier access to graphics. Similarly, another maintainer stated that the graphics did not aid visual inspection and assessment tasks, due mainly to the time required to locate the graphic. He stated that time is crucial in ABDR tasks and the quicker a graphic is found, the better. All agreed that, once found, graphics were helpful in aiding repairs.

Question: Is there ever a time when TO graphics do not aid in maintenance? How?

Routine Maintenance: Only two maintainers responded "yes" to this question. One maintainer commented that the lack of detail in the graphics made them very difficult to use. The graphics did not give him spatial location information for essential components. The other maintainer mentioned a problem with finding parts on a TO graphic. In this case, the organization of the TO appeared to be the leading cause of this problem. For instance, instructions pertaining to a graphic usually precede the graphic by several pages. The maintainer must continually refer back and forth between the text and graphic and integrate the information. This exercise often results in confusion, frustration, and lost time.

ABDR Maintenance: None of the maintainers responded to this question. It would be incorrect, however, to assume a "no" response indicates TO graphics always aid in ABDR maintenance. Typical TOs primarily focus on information related to a particular task. ABDR TOs have information centered on physical and functional means.

Question: Are there any TO graphics that are inadequate or misleading? When?

Routine Maintenance: Although only a few of the maintainers called out specific examples of inadequate and misleading graphics, all stated that they had run across inadequate or misleading graphics at some time in their careers. Graphics for the hydraulic lines, electrical systems, engine bay and fuel cells were deemed particularly inadequate or misleading.

ABDR Maintenance: Opinions differed for this question. Four maintainers said they had never encountered inadequate or misleading graphics, while two others stated they had. Of the maintainers that had, graphics of the engine bay and wings provided inadequate and misleading information. Specifically, the limited perspective and lack of reference points in the engine bay created the problems. Typically, graphics are deemed inadequate or misleading based on perspective. The format of a graphic is just as important as content.

Question: Does experience ever override misleading graphics? When?

Routine Maintenance: All except one maintainer often relied on experience to overcome a misleading graphic. Neither experience nor graphics alone can provide enough information for the maintainers to complete every possible repair. However, when choosing between a TO graphic that does not look accurate and a mental representation based on experience, the maintainers chose their recollections. Of course, this begs the question whether a maintainer could deem a graphic misleading unless there was prior knowledge to draw upon.

ABDR Maintenance: One maintainer had not discovered many misleading graphics, but felt that a potential source of problems existed with the wing graphics. The plane's orientation in the graphics is often unknown. In this case, experience and physical cues help the maintainers determine the graphic's perspective.

<u>Question</u>: Are there any TO graphics improperly drawn or mislabeled? When?

Routine Maintenance: Two of the six maintainers found some graphics to be inaccurate (improperly drawn). The major source of this inaccuracy resulted from the lack of realism between the components as seen in the graphics and on the plane, again found in the graphics of the wing.

ABDR Maintenance: None of the maintainers found any of the ABDR graphics to be improperly drawn or misleading.

<u>Question</u>: Is there ever a time when you reference supplemental material because of poor graphics? What? When?

Routine Maintenance: All six of the maintainers claimed to have referenced supplemental material when graphics were poor. The most popular "supplement" was a similar aircraft. When a graphic was difficult to use, the maintainers preferred to look at another aircraft to get the necessary information; a process that offers more perspectives and a larger field of view than can be found in TO graphics. This technique was usually employed while working on the wings and deep within a bay. One reason the graphics may be less effective is that these locations are shown at unusual perspectives and thus are difficult to comprehend.

ABDR Maintenance: Only two maintainers said they referenced supplemental material. Two maintainers did not respond. In this case, supplemental material was another aircraft. Routing of wiring systems and gaining a proper perspective were two examples requiring supplemental information.

<u>Question</u>: Would TO graphics aid a novice? When?

Routine Maintenance: All the maintainers felt that novices would need to reference a graphic to aid their completion of the repairs. The point was also made that graphics serve as a training tool. Although the graphics may be misleading and incomplete in some cases, they provide more information than can be obtained without them. Obviously, some repairs may require even more instruction than can be found in the TO. In these instances novices often seek help from experts.

ABDR Maintenance: All of the five maintainers that responded agreed that novices would benefit from having graphics. Because of the additional skills required to perform ABDR maintenance, the use of graphics by novices is essential. The TO graphics would be most beneficial when performing small tasks. On larger repairs, the complexity involved exceeds any help that the current graphic's format can provide, so novices must seek additional assistance.

Question: Is there ever a time when mental rotation of a TO graphic is required to complete a job? When?

Routine Maintenance: Four maintainers commented that mentally rotating graphics is required to complete some jobs. For instance, when working on wiring harnesses, the graphics' perspectives were oriented differently that the corresponding aircraft part. As a result, the maintainers perform a mental rotation of the graphic to provide consistency with the part's physical orientation. According to maintainers, the perspectives of the graphics are not always useful and may be misleading. Confusion often results when the perspective of the graphic does not match the perspective of the maintainer. The maintainers stated that for many novices, mental rotation is a skill not easily learned. One maintainer contradicted the other two and stated that he believed all the graphics are in a proper perspective. The final maintainer did not respond to the question.

ABDR Maintenance: For the majority of the maintainers, ABDR graphics required the same level of mental rotation as routine maintenance graphics. Again, the wiring systems and wing portions of the aircraft required the most frequent mental rotation. Two maintainers contradicted each other. One stated that ABDR repairs are more general than routine repairs, thus requiring less mental rotation, while the other stated that ABDR repairs require more mental rotation.

Question: Was there ever a time when you had to change your visualization of a TO graphic to complete a job? When?

Routine Maintenance: All but one of the maintainers answered this question affirmatively. Maintainers approach repairs with a preconceived notion of how to start. The TO graphics are referenced to complete the plan of action. However, the repairs are often not visually consistent. That is, hydraulic lines, wires, bullets, and wing structures may not be oriented like the graphic. Once this realization is made, the maintainer can either change his

mental visualization of the graphic to coincide with the plane or re-orient himself to be consistent with the visualization. To aid in the former, some maintainers will physically re-orient the graphics. Of course, any associated text is now in a non-standard orientation and thus much less readable. The goal of this procedure is to generate graphics visually consistent with the repair.

ABDR Maintenance: Of the three maintainers who responded, all claimed to have changed their visualization of a graphic to complete a job. The justifications for doing this were identical to the ones given when asked the same question with regard to routine maintenance.

Question: Was there ever a time when graphics were unavailable? When?

Routine Maintenance: The majority of maintainers responded that there was never a time that graphics were unavailable. To the best of their recollection, they were never in need of a graphic. Two of the six maintainers recalled, however, a need for an apparently missing graphic. The repair areas included the wing and environmental duct. There were no graphics available to aid them in removing and replacing these items.

ABDR Maintenance: All but one of the five maintainers responded that there was never a need for additional graphics. The one requirement for graphics was to aid in the search for projectiles (objects which have pierced the aircraft's shell).

Question: Would 3D graphics aid in typical/ABDR maintenance? When?

Routine Maintenance: All six of the maintainers gave an overwhelmingly positive response to the potential usefulness of 3D graphics. They stated that this technology would allow them to have more control over the graphics. For example, the graphics could be manipulated to produce the same perspective as that of the repair area on the aircraft. The graphics could also contain more information and realism. Providing different sets of graphics for different types of jobs was another suggestion. The level of detail in the graphic would depend on the job it aided. Overall, the maintainers felt that 3D graphics would better help them identify and understand repairs.

ABDR Maintenance: All but one of the maintainers believed ABDR maintenance would benefit from 3D graphics. They could see that the use of 3D graphics would help in the assessment phase, specifically damage assessment. With the help of 3D graphics, the maintainers

could locate projectiles and the extent of damage by better understanding the plane's structure provided through 3D graphics. Some tasks have to be performed without visual feedback due to limited accessibility compartments, and 3D graphics can provide this otherwise missing information (features not visible). The identification, location, and path of wires could also be conveyed within a 3D graphic. The only maintainer who did not agree that 3D graphics would aid in ABDR maintenance was an electrician. He contradicted another maintainer by saying that wiring repairs would not benefit from this technology. He believed graphics represent parts that have not been damaged and that the only way to properly assess and repair parts is to go directly to the aircraft. He saw no benefit in having 3D graphics.

Question: Would 3D graphics aid a novice? When?

Routine Maintenance: Of the four maintainers who responded to this question, all felt that 3D graphics would aid a novice. One maintainer stated that the current graphics were not that helpful to a novice and that 3D graphics would provide more details, making the jobs easier to perform. The more detailed the graphic, the more helpful they will be to a novice. Another maintainer felt that the use of 3D graphics in training would cut down on training time tremendously. Although this last point has not been validated, the use of 3D graphics in training warrants further investigation.

ABDR Maintenance: Again only four maintainers responded to this question from the perspective of ABDR. Just as before, they all stated that 3D graphics would help novices. The added capabilities 3D graphics provide, such as enlarging and labeling graphics, could only benefit a novice. Because there are so many voids and crevices in the aircraft, maintainers have a difficult time identifying and accessing particular areas. 3D graphics offers a method of "accessing" a concealed area. This feature could prove to be extremely helpful. The ability to change the perspective of a graphic was also desirable.

Question: Which TO graphics need improvement?

Routine Maintenance: All six of the maintainers responded to this question. Graphics showing component removal, wiring and hydraulic diagrams, wings, and flight controls need improvement to produce a more accurate representation of the aircraft. These graphics were selected because of specific deficiencies, but there was a common trend among them. The

majority of the complaints centered on the poor perspective of the graphics and the difficulty of extracting information. Often, maintainers cannot even locate the appropriate graphic. As stated many times, this is the result of the TO manual's poor layout. Their organization was criticized as being confusing and inconsistent.

ABDR Maintenance: Fewer maintainers responded to the same question when asked with regard to ABDR maintenance. Again, the wing graphics were chosen as needing improvement. A maintainer stated that these graphics were cluttered and often presented from unusual perspectives. Another design, side-by-side graphics showing opposite views, also requires a better perspective or labeling to make orientation information clearer with respect to the aircraft. For example, this scenario occurs in graphics of the fuselage. One maintainer stated that the lack of details found in the current graphics make ABDR maintenance tasks even more difficult.

<u>Question</u>: What type of improvement is needed for the TO graphics?

Routine Maintenance: All six of the maintainers answered this question. There were a wide variety of responses. One called for graphics to appear in the same perspective as on the aircraft. The demand for the ability to zoom, peel away or remove, rotate, show color and label components was repeated by virtually every maintainer. There was a stipulation placed on the color feature, in that, if used, colors must closely resemble the colors found on the aircraft. The capability to show a wiring harness or a hydraulic line from start to finish was a desired improvement. Along with the capability of labeling components, additional information should be provided, such as the structural makeup, sub-components, and dimensions. Several unique features also surfaced, for example, a search feature that would allow the maintainers to locate a part or graphic instantly. The ability to simulate damage in the 3D graphic so an engineer could see the damage rather than just rely on the maintainer's description could lead to a more efficient repair process.

ABDR Maintenance: The six maintainers had similar requests in response to this question regarding ABDR. The most popular suggestion for improvement was a feature not considered by the research team. All of the maintainers called for some type of tutorial or help system that would offer hints for difficult repairs or store experts' solutions to uncommon repairs. The hints would provide help regarding repair procedures for a particular area. These hints would be

gathered through experience, stored in the computer along with 3D graphics and relayed to the maintainer performing the repair. One maintainer suggested that damage be assessed and typed into a computer, which would recommend an ABDR repair procedure (artificial intelligence).

<u>Question</u>: Do you ever visualize peeling away levels of surface? When?

Routine Maintenance: Four of the six maintainers responded yes to this question. All had either performed a mental visualization effectively peeling away layers of the aircraft, such as panels, wires and wing surfaces, and thought that a 3D graphic would take the place of having to perform this function mentally.

ABDR Maintenance: Again, only four responses were recorded for this question. Peeling away the skin of the aircraft and the removal of components were the most typical scenarios reported.

<u>Question</u>: Is full manipulation of 3D graphics required?

Routine Maintenance: A little over half of the maintainers answered this final question. Three felt that full manipulation capabilities of the 3D graphic are required to use 3D graphics to their fullest extent. The other maintainer stated that once a graphic gets down to a specific level of detail, only three views would be needed to complete a job.

ABDR Maintenance: None of the maintainers responded to this question when asked in the ABDR session.

Capability Requirements

The six maintainers who participated in the CTA provided numerous comments and suggestions as to the use of current TO graphics and the potential use of 3D graphics in maintenance tasks. All of the maintainers stated that the current TO graphics do aid in performing tasks but could use some improvement. The overall consensus was that 3D graphics would provide an added benefit. A list of requirements that were deemed essential to the use of 3D graphics has been culled from the maintainer's comments.

1. Full manipulation of a 3D graphic

   This feature would allow users to manipulate the graphic in any manner that suited the repair purpose.

2. Labeling of components

   This feature would help in the identification and location of components within a graphic.

3. Removal of components capability

   This feature would allow components to be removed so that items located behind them could be viewed. This would be particularly helpful in the assessment phase.

4. Zoom

   The zoom feature would allow users to get a closer view of a particular component. However, this feature is useful only if the closer view provides increased detail.

5. Rotate

   This feature would give the maintainers the ability to view a component in the best possible position.

6. Display of colors

   The use of color with 3D graphics is beneficial. The components can either be color-coded or colored, as realistically as possible, as they appear on the aircraft.

The maintainers also called for a variety of other features that would aid both a novice and expert in their maintenance task. Several of the maintainers suggested that separate sets of graphics pertaining to different types of jobs would be an efficient way to organize the TO information. A "wide-angle" view would also allow maintainers to see components in an electronic format that would typically be missing from a current TO graphic. Furthermore, the maintainers suggested that more details than those provided by current TO graphics are needed to further aid in maintenance procedures.

Finally, scale drawings along with the ability to show damage on the 3D graphic would allow the maintainers to draw damage on a graphic just as it exists on the aircraft. This would give the engineer a better idea of the extent of the damage.

Another feature greatly desired by the maintainers was the ability to search a TO for a particular component by typing the name and/or part number into the computer and having that part appear highlighted in the 3D graphic. They also mentioned several times the desire to type in the location and extent of the damage and have the computer recommend repairs or provide hints and tips of things to do. These hints or tips would definitely prove useful for both the novice and experienced maintainers. For example, ABDR maintainers are often qualified for a variety of system repairs but may typically only work on a few particular systems. As a result, there may be systems and system repairs with which the maintainer may be less familiar. Hints to guide the appropriate repair procedures would be useful.

Finally, several maintainers commented that 3D graphics would cut down on training time tremendously. Although a supplemental study would be needed to determine if this claim could be validated, the maintainers' emphatic belief indicated that further study is warranted.

3D FILE FORMATS

Review of Current 3D File Formats

During this part of the study, the team identified and ranked industry and DoD 3D file formats. In order to rank the file formats, a set of weighted criteria were developed and used to give each of the file formats a numerical ranking. Details of the criteria and ranking results are provided in the following sections. The team determined that there are over 150+ common 3D graphics file formats available, each with their own set of features and characteristics.

The team was faced with one of three possible choices for identifying and evaluating the industry and DoD file format standards:

- Evaluate all of the 150+ file formats through the entire set of evaluation criteria.
- Pass all of the 150+ file formats through a small subset of the evaluation criteria, focusing on the criterion with a "high" importance value.
- Leverage the extensive knowledge of virtual reality (VR) and computer graphics systems the team possessed to logically reduce the number of available file formats to a workable subset in line with the scope of this effort.

The first choice, pass all file formats through the full set of criteria, was immediately discarded due to the limited amount of time and money allotted to the effort. Evaluating the 150+ file formats could be considered a never-ending investigation of its own, since the file formats are constantly being updated, and new ones developed.

The second choice, while appealing, was also discarded due to time constraints as well as the focus of the project: the 3D viewer. The file formats chosen for the investigation do have some merit and are important because they contain a set of data the viewer will use. However, the viewer typically dictates the file format as discussed in the section titled "3D VIEWERS." Therefore, the decision was made to focus more on identifying a larger number of viewers at the expense of evaluating a larger number of 3D file formats.

The team decided on the third choice, to rely on the team's extensive collective knowledge of the computer graphics and simulation arena. The five team members who worked on identifying and evaluating the file formats collectively had over 20 years direct experience in computer graphics. Additionally, members of the AFRL/HES division with computer graphics experience were solicited to help select the list of file formats that were finally evaluated.

Identification of 3D File Formats

The file formats finally chosen by the team had one or more of the following features. One, the format had some history of extensive use in the field of VR and 3D modeling. Two, the format was created by a software package with a history of extensive use in the field of VR and 3D modeling. Three, the format promoted itself as a format with open standards. Additionally, the format was chosen if it was recommended by a military branch concerned with VR or computer graphics.

Table 1 lists the industry standard 3D file formats as determined by the research team. The first column lists the name of the file. The second column lists the common file extensions associated with the particular file format. Finally, the last column identifies the company or individual responsible for the development and support of the file format.

Table 1. Industry Standard 3D File Formats

Format Name	File Extension(s)	Creator
3DS (3D Studio)	.3ds	Kinetix/ AutoDesk, Inc.
DWB (Designers Workbench)	.dwb, .dwba	Coryphaeus Software
DXF (Drawing Interchange File)	.dxf	AutoDesk Inc.
FLT (OpenFlight)	.flt	Multigen
NFF/ ENNF (Neutral File Format/ Extended Neutral File Format)	.nff, .enff	Eric Haines
OBJ (Wavefront Object)	.obj, .mod	Wavefront/ Alias Technologies
POV (Persistence Of Vision)	.pov	POV-Ray Team
VRML (Virtual Reality Modeling Language)	.vrml, .wrl	Standard based upon SGI's Open Inventor format

In addition to the seven commercially-produced 3D file formats, the team identified two potentially viable DoD 3D file formats. Table 2 summarizes the DoD file formats identified.

Table 2. DOD 3D File Formats

Format Name	File Extension(s)	Creator
SEDRIS (Synthetic Environment Data Representation & Interchange Specification)	None, format is still being defined	Defense Modeling and Simulation Office (DMSO)
IGES (Initial Graphics Exchange Specification)	.jgs	IGES/PDES Organization

Evaluation Criteria for 3D File Formats

A set of weighted criteria was developed to evaluate and rank each of the file formats identified. This list of criteria, which encompasses many uses and capabilities, was created by focusing on the following needs which were applicable to the aircraft maintenance task:

1) The format has some feature which enhances realism of the simulated environment.

2) The format has some feature which allows for manipulation of the simulated environment.

3) The format has some feature which enhances its use, its distribution, or its ability to be modified.

As in the selection of file formats, the list of evaluation criteria was distributed to members of AFRL/HES division for comment. Table 3 summarizes the criteria used to evaluate and rank each of the file formats.

For each of the criterion listed in the first column of Table 3, there is an associated weight and a set of sub-criteria. The weight associated with each criterion signifies the relative importance of that particular criterion. Each of the criterion was assigned an integer weight value between 10 and 1, 10 being the highest (most important) and 1 being the lowest (least important.) These weights were determined by features requested by HESR representatives, requests from the group of maintenance personnel during the CTA, and the need to produce a realistic, modifiable simulated environment that could be manipulated.

For example, the criteria "Text" was given a weight of 8 because textural information was highly recommended by the customer. "Groupings" was given a 9 because the capability to

represent complex objects was highly prized for realistic simulations. "Color" was given a 7 because several maintenance personnel liked the idea of marking items in color. On the other side of the list, items such as "Wireframe" were given low scores because those items were not mentioned by the customer or maintenance personnel and do not lend themselves well to producing the most realistic environments.

To be as objective as possible, each criterion was broken down into a series of sub – criteria which represented capabilities that the main criteria can contain. Each sub-criterion, shown in the third column of Table 3, is separated with a square box. For example, the criterion "Polygon" consists of four sub criteria: "Convex, N-sided, Concave, and Decaled." The numerical value listed prior to each sub-criteria is the specific score that a particular sub-criterion contributes to the overall score of the criterion. The sum of the numerical values associated with each of the sub-criteria always adds to a value of 10. The score a file format received for a particular criterion was calculated as follows.

1) Determine which of the sub-criteria were fulfilled by the file format

2) Add the numerical values of the satisfied sub-criteria, a value between 0-10.

3) Take the value obtained from step 2 and multiply by the weight factor

For example, assume that file format X supported convex and N-sided polygons but lacked support for concave and decaled polygons. File format X would have received a score of 80 [(6+2) * 10] for the criterion polygons. For the hypothetical file format X, 80 is considered the "raw score" for this particular criterion.

While realism and manipulation play a much larger part in the 3D viewer criteria, they also play a part in the file format ranking. The file format, which contains the sets of data, allows realism and manipulation of the environment in the 3D viewer.

Table 3. 3D File Format Evaluation Criteria

Criterion	Wt	Sub-Criteria
Polygons	10	❑ *(6) Convex*: Polygons stored can have a convex shape. ❑ *(2) N-sided*: Polygons stored can have an unlimited number of sides. ❑ *(1) Concave*: Polygons stored can have a concave shape. ❑ (1) *Decaled*: Polygons can be stored one within another on the same plane. Render order information is included, allowing the polygons to be rendered properly.
Groupings and Links	9	❑ *(6) Grouping*: The stored information represents that one or more polygons can be considered as a logical group with a common transformation matrix. ❑ *(3) Links to external files*: There can be links to files of the same format, which impart additional grouping information. ❑ *(1) Named groupings*: Each grouping has a descriptive name.
Lines and Lines styles	8	❑ *(7) Lines*: Lines are stored in the format as a primitive. ❑ *(2) Patterns*: Information associated with the line primitive pattern is stored. ❑ *(1) Thickness*: Information associated with the line thickness is stored.
Text	8	❑ *(5) Primitive*: Text can be stored as a primitive. ❑ *(2) Size*: Information associated with the text's size is stored. ❑ *(1) Font*: Information associated with the text's font is stored. ❑ *(1) Direction*: Information associated with the direction the text is oriented is stored. ❑ *(1) Justification*: Information associated with the text's justification is stored.
External links to text	8	❑ *(10) Text*: Links to files, which contain text information, are stored.
External links to pictures	8	❑ *(10) Pictures*: Links to files which contain 2D bitmap information are stored.
Mathematical Objects	7	❑ *(3) Common 3D objects*: Spheres or boxes can be stored as primitives. ❑ *(2) Common 2D objects*: Ellipses or n-sided figures can be stored as primitives. ❑ *(2) Less common 3D objects*: Torii, or discs, or cylinders, or cones, or surfaces of revolution can be stored as primitives. ❑ *(1) Less common 2D objects*: Splines or arcs can be stored as primitives. ❑ *(1) Rare 3D objects*: Fractals or mathematical surfaces can be stored as primitives. ❑ *(1) Constructive Solid Geometry*: Logical operations (such as AND, OR) are stored in the format for the purpose of creating a new object out of a set of mathematical objects.
Color Information	7	❑ *(7) Unlimited colors*: R, G, B values or an unlimited number of color table values are stored. ❑ *(3) Limited colors*: A limited number of color table values are stored.
Transparency	7	❑ *(10) Transparency*: A transparency value is stored with a primitive.
Material Properties	6	❑ *(2) Specular*: Specular lighting components are associated with a primitive. ❑ *(2) Diffuse*: Diffuse lighting components are associated with a primitive. ❑ *(2) Ambient*: Ambient lighting components are associated with a primitive. ❑ *(1) Emissive*: Emissive lighting components are associated with a primitive. ❑ *(1) Shininess*: Shininess lighting components are associated with a primitive. ❑ *(1) 2D Bump mapping*: A 2D set of data representing a bump map is associated with a primitive. ❑ *(1) 3D Bump mapping*: A 3D set of data representing a bump map is associated with a primitive.

Criterion	Wt	Sub-Criteria
Textures	6	❑ *(6) 2D Texture mapping*: A 2D set of data representing a texture map is associated with a primitive. ❑ *(3) Draw style*: A draw style representing a particular repetitive pattern is associated with a primitive. ❑ *(1) 3D Texture mapping*: A 3D set of data representing a texture map is associated with a primitive.
Normals	5	❑ *(8) Vertex normals*: Normal vectors are stored and associated with a primitive's vertex. ❑ *(2) Face normals*: Normal vectors are stored and associated with a primitive's face.
Viewing Information	5	❑ *(4) Multiple views*: More than one specified view angle and position are stored. ❑ *(3) One view*: A single specified view angle and position is stored. ❑ *(3) Fly-though*: More than one specified view angle and position is stored, and a pattern representing a fly-though sequence is stored.
Efficiency Patterns	5	❑ *(2) Polygon*: Polygons can be stored in strips, fans, and meshes. ❑ *(2) Vertex list*: Vertices are stored in a list. ❑ *(2) Tables*: Color tables and material tables are supported. ❑ *(2) Global lists*: Vertex lists, or texture lists, or normal lists are considered global and allow other groupings to access them. ❑ *(1) Texture vertex list*: Texture coordinates are stored in a list. ❑ *(1) Normal list*: Normal vectors are stored in a list.
Render Order	4	❑ *(7) Strict order*: Values associated with the rendering order of primitives are stored. The values are in a format, which indicates the exact order that all primitives will be rendered in. It is possible to have strict order without having the capability for loose order. ❑ *(3) Loose order*: Values associated with the rendering order of primitives are stored. The values are in a format which indicates a rough order (front, back, or grouping levels) that all primitives will be rendered.
Openness and Support	4	❑ *(5) Governing group*: The group, which dictates features, changes, additions, and implementation of the format is a fairly impartial one. ❑ *(4) Support*: The group, which governs the file format and a subset of users, offer freely available support. ❑ *(1) Specifications*: The group, which governs the file format, allows the full file format specifications to be known and freely distributed with no legal bindings.
Measurement Units	3	❑ *(4) Linear per primitive*: English and metric linear units are associated with a primitive. ❑ *(3) Angular per primitive*: Radian and degree angular units are associated with a primitive. ❑ *(2) Linear per file*: English and metric linear units of measure are associated with all primitives in the file. ❑ *(1) Angular per file*: Radian and degree angular units of measure are associated with all primitives in the file.
Points	3	❑ *(9) Points*: Points are stored in the format as a primitive. ❑ *(1) Size*: Information associated with the point size is stored.
Switches, LOD, Morphing	3	❑ *(4) Switches*: Several versions of a primitive's geometry are stored in the format. ❑ *(3) Named States*: Each state has a descriptive name. ❑ *(2) LOD*: Distance information is stored with the versions to indicate when to switch between states. ❑ *(1) Morphing*: The versions are marked in some way to allow a smooth transition between the versions of the geometry.

Criterion	Wt	Sub-Criteria
Bounding/ Culling Information	3	❑ *(3) Complex boundaries*: Information describing a bounding area of a complex shape around the primitive's geometry is stored. ❑ *(7) Mathematical object boundaries*: Information describing a bounding area of a simple 2D or 3D mathematical object shape around the primitive's geometry is stored.
User Extensible	3	❑ *(4) Customization*: The file format allows the definition of sets of data, the function of which is not defined in the file format specifications. File formats, which extend themselves in this manner through comment fields, are excluded. ❑ *(4) Code Sets*: The file format can contain some type of computer language. ❑ *(2) Field extensibility*: The file format contains some fields which the user can store information.
Wireframe	3	❑ *(7) Wireframe*: Any of the primitives elsewhere in the criteria list can be stored specifically as a wireframe. ❑ *(2) Patterns*: Information associated with the pattern of the wireframe is stored. ❑ *(1) Thickness*: Information associated with the thickness of the wireframe is stored.
Animations/ Articulations	2	❑ *(6) 3D Animation*: An animation sequence created by changing transformation parameters of primitives is stored. ❑ *(3) 3D Articulation*: Parameters representing limits to degrees of freedom for primitives are stored. ❑ *(1) 2D Animation*: An animation sequence created by sequencing through texture maps or material property patterns on a primitive's surface is stored.
Space Partitioning	2	❑ *(10) Partitioning*: Any form of space partitioning information is stored.
Light Sources	2	❑ *(4) Infinite light source*: Infinite light source parameters are stored. ❑ *(4) Local light source*: Local light source parameters are stored. ❑ *(1) Spotlight light source*: Spotlight light sources parameters are stored. ❑ *(1) Color*: RGB values or color table values can be associated with a light source.
Stability of Format	2	❑ *(8) Compatibility*: All new formats are backward compatible with previous versions of the format. ❑ *(2) Updates*: The governing group changes the format specifications less than once a year.
Size of 3D Files	2	❑ *(10) Size*: The size, in kilobytes, of several task-related objects stored in the format.
Links to sound files	2	❑ *(10) Sound*: Links to external files, which contain digitized sound information, are supported.
Comments	1	❑ *(7) Nonrestrictive comments*: There exists some comment marker, which allows the inclusion of comments at any position in the file. ❑ *(3) Restrictive comments*: Comments can be placed in certain fields in the structure:

3D File Format Evaluation Results

This section contains the results of evaluating each of the identified file formats using the evaluation criteria listed in Table 3. Table 4 summarizes how each of the file formats performed in the evaluation. The file formats are listed across the top of the table starting in the second column. The first column of the table identifies the criterion. The numerical values for each of the file format evaluation criterion combinations represents the raw score. The raw score is

defined as the sum of the satisfied sub-criteria times the weight for the particular criterion. The last two rows of Table 4 list the raw score total and the normalized score for each of the file formats. The raw score total was calculated by adding all of the raw scores for each of the criteria. Dividing the total raw score by the total possible points, in this case 1260, produced a normalized score for each of the file formats (a score between 0-100%, where 100% indicates the file format met all the criteria).

Table 4. 3D File Format Evaluation Results

	VRML	SEDRIS	DWB	FLT	POV	IGES	3DS	DXF	OBJ	NFF/ ENNF
Polygons	100	100	100	100	90	90	60	70	90	90
Groupings and Links	90	90	63	90	90	90	63	90	90	0
Lines and Linestyles	56	56	0	0	0	80	0	80	56	0
Text	80	48	80	64	72	80	0	80	0	0
External Links to Text	80	0	0	0	0	0	0	0	0	0
External Links to Pictures	80	80	80	0	0	0	80	0	0	0
Mathematical Objects	35	42	7	0	49	70	0	35	14	49
Color Information	70	70	70	21	70	70	70	21	0	70
Transparency	70	70	70	70	70	0	70	0	70	0
Material Properties	48	54	48	48	48	0	54	0	36	42
Textures	54	54	54	54	54	18	36	18	60	0
Normals	50	50	50	40	40	10	0	0	40	50
Viewing Information	50	35	35	50	15	35	50	15	0	15
Efficiency Patterns	20	50	10	40	10	30	25	10	30	0
Render Order Information	12	40	0	12	0	12	0	40	0	0
Openness and Support	40	40	20	0	20	20	0	20	20	20
Measurement Units	0	12	6	6	0	27	0	30	0	0
Points	27	27	30	0	0	30	0	30	27	0
Switches, LOD, Morphing	30	30	27	30	0	0	3	0	0	0
Bounding / Culling Info.	30	21	21	21	30	0	21	0	0	0
User Extensible	30	12	18	6	0	12	0	12	0	0
Wireframe	0	0	30	30	0	0	24	0	0	0
Animations / Articulations	14	20	14	20	14	0	12	0	0	0
Space Partitioning	20	20	20	20	0	0	0	0	0	0
Light Sources	20	20	20	20	12	0	12	0	0	10
Stability of Format	0	0	20	4	20	20	16	20	20	20
Size of 3D Files	0	0	0	0	0	0	0	0	0	0
Links to Sound Files	20	20	20	20	0	0	0	0	0	0
Comment Fields	10	3	10	10	10	3	0	3	10	10
Raw Score Total	1136	1064	923	776	714	697	596	574	563	376
Normalized Score (0-100)	82.3	77.1	66.9	56.2	51.7	50.5	43.2	41.6	40.8	27.2

Descriptions of Identified File Formats

This section provides a brief description of each evaluated file format, including details on how the particular file format performed against the evaluation criteria. The name of the file format is presented using underlined type followed by the description. The descriptions are presented in ascending order based on the overall score the file format received (see Table 4).

Virtual Reality Modeling Language (VRML), 82.3 %

The Virtual Reality Modeling Language is an attempt to define an open, multi-platform, virtual reality language for the WorldWide Web (WWW). ASCII files containing this language are used in conjunction with VRML browsers, allowing a Web user to move through a simulated environment.

VRML was originally developed by Silicon Graphics, Inc., which used its Open Inventor file format as the basis for VRML. VRML was modified to be Web friendly in Version 1.0 of the file format specification released on May 26, 1995. The current version (2.0) was released August 4, 1996 by the VRML Architecture Group (VAG). The VAG is a collection of companies that decide what and when changes are made to the format specification. The specification for the file format is available on the Internet and other published sources. Support is available from the numerous companies that comprise the VAG. VRML was recognized as an ISO and IEC standard in December 1997.

VRML is popular not only because it can be used on the WWW, but because it has many powerful features, including the specification of a variety of different kinds of individual objects and groups of objects; text specification; material and color compositions and lighting specification; specification of interactive behavior; Level Of Detail (LOD); and animation. A feature that sets VRML apart from most other 3D file formats is that it allows users to extend its capability.

Although VRML is a powerful tool for specifying 3D scenes, it has some shortcomings. These include a lack of support for measurement units and complex and uncommon 2D and 3D primitive objects.

Synthetic Environment Data Representation & Interchange Specification (SEDRIS), 77.1%

The SEDRIS data model is being developed by several government agencies (including the Defense Modeling and Simulation Office) as well as 13 private simulation and government contractor companies. Although the SEDRIS data model is not yet fully defined, it incorporates classes of data, relationships between the classes, and primitive data types – in other words, it can be considered a language.

Features of SEDRIS encompass nearly all the criteria required for this investigation. Its class structure gives it a strong groupings and links capability, and most of the basics such as polygons, color information, and transparency are included. The current missing features include external links to text as well as weak support for measurement units, but these may eventually be included in the final revision.

Designer's Workbench (DWB), 66.9%

The Designer's Workbench format is maintained by Coryphaeus Software, Inc. for use with its 3D Database Modeler. The modeling package, Designer's Workbench, creates 3D models for real-time visual simulation. The current version of the format is 4.0, which was released in September 1997. Files are in a binary format for better disk space utilization. The physical layout is designed to allow any unrecognized entity to be easily ignored.

The conceptual layout is hierarchical, which makes this format a little more difficult to create and read, but adds a great deal of power. This file format supports most of the basic and higher level constructs desired in a 3D file format. It has very good support for polygons, groupings, text, colors, transparency, material properties, textures, normals, switches, LOD, animations, articulations, and light sources. Some of the major constructs missing from the format include lines, external links, mathematical objects, and efficiency patterns. The DWB format contains most, if not all, of the fields needed when creating models for real-time simulation but is missing some of the fields necessary to make it an excellent general-purpose 3D graphics file format.

OpenFlight (FLT), 56.2%

The OpenFlight 3D file format was originally developed by Multigen, Inc. for use in their 3D modeling and real-time graphics software. The release of the file format into the public domain, coupled with the versatility and features of the format itself, have made OpenFlight one of the most widely-used file formats in the real-time simulation and computer gaming industry.

OpenFlight's main strength is its organized hierarchy of polygonal objects, with generous support for textures and material properties. Since all simulation environments are typically represented as a collection of polygons, this approach provides the most flexibility. OpenFlight also provides several efficiency features, such as global vertex lists, normal lists, and color tables, in addition to being a binary format to conserve space. OpenFlight also includes features to improve display speed, such as level-of-detail information and bounding boxes. OpenFlight is missing capabilities such as linestyles and external links to text and pictures.

POV-Ray (POV), 51.7%

The POV file format was developed for use in Persistence Of Vision's Ray-Tracer (POV-Ray), a software program developed by the POV Team (an independent group of software developers) that generates high-fidelity images from 3D models. As with most ray-tracers, POV-Ray does not display 3D models in real-time, but instead is used to generate a single image of a 3D model with extreme detail, or a series of detailed images that can be replayed like a movie. POV-Ray primarily uses mathematical objects like spheres and cones rather than arbitrary groups of polygons because mathematical objects are easier to process in the ray-tracing algorithms.

The POV file format supports enough features to be useful to the aircraft maintenance task, with support for polygons, object groupings, text, and many types of 3D objects. It also supports textures, material properties, and arbitrary colors. However, the real strengths of POV lie in its extensive support of surface properties like transparency and reflectivity, and extensive camera properties like focal blur and atmospheric attenuation, which were deemed unnecessary for the aircraft maintenance task. However, like OpenFlight, the POV file format does not have the capability for linestyles or external links to text and pictures.

Initial Graphics Exchange Specification (IGES), 50.5%

The IGES file format is an ANSI standard maintained by the IGES/PDES organization. The function of IGES is to set up a series of structures to exchange product definition data. In other words, it's a file format mainly used by computer-aided design and manufacturing systems (CAD/CAM).

The IGES format covers most of the criteria basics, such as polygons, groupings, lines and linestyles. Due to its CAD/CAM background, it satisfies most of the basic criteria, covers an incredible number of mathematical objects, and has a strong measurement unit criteria score. Unfortunately (also due to its background), it's weak in many of the criteria needed to produce a realistic simulated environment, such as material properties and textures.

3D Studio (3DS), 43.2%

The 3DS file format is a proprietary format owned by AutoDesk. Made popular by the modeling software 3D Studio (and, to a lesser extent, AutoCAD), 3DS is a fairly commonplace file format. Although files using the (binary) format are commonplace, it's surprisingly difficult to obtain the file format specifications from AutoDesk. Once obtained, 3DS shows its physical layout of the file format as a series of "chunks" which can have a hierarchical structure.

While 3DS is popular, it doesn't offer much to this investigation. It has limited polygon and grouping capabilities, and has the full criteria for links to pictures, color information, transparency, and viewing information. It cannot handle lines, text, external links to text, or mathematical objects.

Drawing Interchange Format (DXF), 41.6%

Similar to IGES, DXF is used for CAD applications; specifically, DXF is the internal structure for AutoDesk's popular AutoCAD software. Previously only a 2D format, DXF first had its capabilities extended in 1985 to encompass simple 3D entities. Further revisions of the format have extended the 3D DXF so that it can contain more complex entities. The physical layout of the file format is well-defined, with certain sections including AutoCAD-specific

information, and other sections containing information on the 2D/3D structures to be displayed in the simulated environment.

Due to its CAD background, DXF provides a strong basis for CAD-related criteria such as lines, text, measurement units, and points. However, like IGES, it lacks many of the criteria needed to create a convincing simulated environment, such as color information, material properties, normals, animations, and light sources.

Wavefront (OBJ), 40.8%

The OBJ file format was developed by Wavefront. OBJ is a very stable format, and can be as stored as ASCII format files (.obj) and binary format files (.mod). OBJ files define geometric and other properties for objects in Wavefront's Advanced Visualizer application. The file format has a free-form organization. OBJ files store geometric objects composed of lines, polygons, and free-form curves and surfaces. As far as support for its 3D file format is concerned, Wavefront maintains a toll-free support number and Bulletin Board System (BBS) for its customers. There are also many Wavefront user groups.

Although the OBJ file format is used by many popular applications, as a 3D file format it has many shortcomings. Among them are lack of text support; provisions for specular, diffuse, and ambient material properties only; lack of animation or articulation; and no support for wireframe or light sources.

Neutral File Format / Extended Neutral File Format (NFF / ENFF), 27.2%

The Neutral File Format is maintained by Eric Haines of 3D/Eye Inc. The format was written to have minimal constructs that could be used for testing rendering algorithms. It is intended to be used with the Standard Procedural Database (SPD) software package. The first draft of the format was created in October 1988, and revisions and extensions were made until the most recent revision in April 1993. Because the format is minimal, its ASCII text files are simple to create and read.

The format supports most of the basic constructs necessary to create geometry, colors, shading, lighting, and a viewpoint. The format is missing many higher-level constructs such as

groupings, lines, text, textures, measurement units, points, switches, levels of detail (LOD), animations and articulations. NFF is very useful for writing simple test cases for testing rendering algorithms, but is missing many of the constructs necessary for use as a general-purpose 3D graphics file format.

3D VIEWERS

Identification of 3D Viewers

The purpose of this phase of the 3D Graphics Investigation was to find the ideal 3D viewer: a package that would allow the data contained in a 3D file format to be presented onscreen in a 3D simulated environment. Such a package can be found in nearly any field that uses computers and data visualization.

The following types of software packages were considered as likely candidates for an ideal 3D viewer: 3D modeling software, CAD packages (including design prototyping systems as well as drafting and architectural systems), and virtual reality (most commonly VRML) software. Upon initial inspection, these fields appeared to offer products that closely matched the needs of the investigation. However, even when limited to these areas, the marketplace offered several hundred software packages from which to choose. To make an objective choice between the good and mediocre 3D viewers, the necessary criteria for a 3D viewer were defined. The criteria were based on three fundamental themes:

1) The ideal viewer will use graphics technology that produces a realistic, simulated 3D environment that could be manipulated.

2) The ideal viewer will contain all the features requested by the group of maintainers during the CTA.

3) The ideal viewer will contain all the features requested by HESR representatives, including low cost and the ability to interface with common WWW browsers. (It was assumed that future electronic TOs would be authored in HTML, allowing both the 3D graphics and textual TO information to be tightly integrated. In addition, this software would reside on a large number of machines, indicating the need for a low price.)

The target hardware platform for the 3D viewer was an Intel Pentium-based laptop computer operating at 200 Mhz on a Windows platform.

3D Viewers Identified

Using the WWW as the primary source of information, the team identified 19 candidate 3D viewers, listed in Table 5. The first column of the table lists the name and version of the

viewer, the second column lists the name of the company responsible for developing/supporting the viewer, the third column indicates whether the viewer is a plugin, and the last column lists a universal resource locator (URL) link for product information and demonstration versions. Free evaluation copies were available for all but one of the viewers (3D Studio Max.)

One popular CAD software package absent from the list. AutoCAD by Autodesk, was considered and researched but not evaluated. The team conducted a meeting with a local value added re-seller (VAR) of the AutoCAD product. After thoroughly explaining the functionality required of the 3D viewer for the task, the team and the VAR collectively determined that the AutoCAD product was not a viable candidate for this study. The 3D capability of AutoCAD is centered primarily around wireframe models.

Table 5. Identified 3D Viewers.

Viewer Name	Company Name	Plug-in	URL Link
3D View 2.1	Actify, Inc.	No	http://www.actify.com/
Quicktime VR 2.1.2	Apple Inc.	Yes	http://www.apple.com/quicktime/qtvr/
Cosmo Player 2.0	Silicon Graphics	Yes	http://cosmosoftware.com/
Community Place VRML 2.0 D2	Sony	Yes	http://vs.sony.co.jp/
V-Realm Browser 1.1 Build 1	Integrated Data Systems	Yes	http://www.ligos.com/
World View 2.0	Intervista Software, Inc.	Yes	http://www.intervista.com/worldview
Platinum WIRL 1.0 Beta G	Platinum Techonology, Inc.	Yes	http://www.platinum.com/products/appdev/vream/wirl_ps.htm
NetAnimator 1.0 Release 3	Geometric Software Services Co.	Yes	http://www.gsslco.com/
3DSpace Assistant 2.0 Template	Graphics Software Inc.	No	http://www.tgs.com/
Beyond 3D Extreme 2.01 beta	Uppercut Software	No	http://www.beyond-3d.com/
OZ Virtual 2.0b3	OZ Interactive	Yes	http://www.oz.com/
Realiview / Realimation 4.3	Datapath	Yes	http://www.realimation.com/
ConceptCAD 3.1 TestDrive	Virtus Corporation	Yes	http://www.virtus.com/
Virtus Player 3.0	Virtus Corporation	No	http://www.virtus.com/
Cult3D 1.1	Cycore Computers	Yes	http://cult3d.com/
Community Client 3D 3.02	Blaxxun Interactive	Yes	http://www.blaxxun.com/
ActiveCGM Browser 5.0	InterCAP Graphics Systems	Yes	http://www.intercap.com/
3D Studio Max 1.2	Kinetix / Autodesk	No	http://ktx.com/
World Up Player Release 4	Sense8	Yes	http://www.sense8.com/products/download.html
Quick3D Beta	PlasticThought	Yes	http://www.PlasticThought.com/Quick3D_about.html/

3D Viewer Evaluation Criteria

As was done for the file format evaluations, a set of weighted evaluation criteria was developed to evaluate the 3D viewers. Table 6 lists the evaluation criteria used. The same format and process used to develop the evaluation criteria for the file formats was used to develop the viewer evaluation criteria.

Similar to the evaluation of the file formats, a set of weighted criteria was developed. This list of 3D viewer criteria was created by focusing on the following needs:

1) The 3D viewer has some feature which enhances realism of the simulated environment.

2) The 3D viewer has some feature which allows for manipulation of the simulated environment.

3) The 3D viewer has some feature which enhances its use, its distribution, or its ability to be modified.

As was completed with the file formats, each of the criteria was given a weight factor between 1 and 10, depending on its relative importance. These weights were determined by features requested by HESR representatives, requests from the group of maintainers during the CTA, and the need to produce a realistic, modifiable simulated environment that could be manipulated. Next, each of the criteria was further broken down into one or more sub-criteria. For a detailed explanation of how the following table was used to score each of the viewers please refer to the section titled, "Identification of 3D File Formats."

Table 6. 3D Viewer Evaluation Criteria.

Bolded criteria indicate "first pass" scoring system; all criteria were used in "final pass" scoring system

Criteria	Wt.	Sub Criteria
Cost	10	❑ *(5) Free*: The 3D viewer is free. ❑ *(4) Low price*: The 3D viewer retails for less than $100. ❑ *(1) High price*: The 3D viewer retails for less than $500.
Perspective View	10	❑ *(2) Perspective view*: The viewer allows the simulated environment to be shown in a perspective view. ❑ *(2) Clip planes*: The far and near clipping planes can be modified. ❑ *(2) Single view manipulation*: A single movement paradigm is supported. ❑ *(2) Multiple view manipulation*: Multiple movement paradigms are supported. ❑ *FOV*: The field of view can be modified. ❑ *(1) Collision detection*: The viewer supports the ability to both move though and be blocked by primitives.
Stability/ Robustness	10	❑ *(10/X) Test number X*: The viewer never quits unexpectedly or crashes while running a test.
Extensibility	10	❑ *(5) User Extensibility*: The user can add in new, user-created functionality to the capabilities of the viewer. ❑ *(5) Vendor Extensibility*: The user can add in new, vendor-created functionality to the capabilities of the viewer.
Groupings	10	❑ *(3) Groupings*: In the viewer, one or more primitives can be considered as a single group. ❑ *(2) Named Groupings*: The descriptive group names can be displayed to the user. ❑ *(2) Manipulation*: The user can place the groupings at other locations in the world. ❑ *(2) Show groupings*: Groupings can be displayed or hidden from view. ❑ *(1) Articulation*: Groupings can have articulation limits.
Polygon Support	9	❑ *(8) Polygon support*: The viewer supports displaying the environment as a set of 3D polygonal surfaces. ❑ *(2) Backfacing*: The viewer supports backfacing.
Run Time Speed	8	❑ *(10/X) Test number X*: The viewer displays the environment within a set of update rate limits. Update rates 1 Hz or higher are considered acceptable.
WWW Plug-In	8	❑ *(8) Plug-In*: The viewer is a plug-in to a World Wide Web browser. ❑ *(2) Stand-alone*: The viewer can, in addition to running as a plug-in, run as a stand-alone viewer.
Orthogonal View	7	❑ *(3) Orthogonal view*: The viewer allows the simulated environment to be shown in an orthogonal view. ❑ *(2) Camera location*: The viewer allows the camera location to be moved in an orthogonal view. ❑ *(2) Camera rotation*: The viewer allows the camera rotation to be changed in an orthogonal view. ❑ *(2) Size of view*: The viewer allows the capability to zoom in and out from the position of an orthogonal view. ❑ *(1) Clip planes*: The far and near clipping planes can be modified in an orthogonal view.

Criteria	Wt.	Sub Criteria
Software Support	7	❑ *(4) Support*: The group that created the viewer offers support on viewer capabilities. ❑ *(3) Unlimited free support*: The group that created the viewer offers free support and instructions on viewer capabilities ❑ *(2) User support*: A subset of users offers freely available support and instructions on viewer capabilities. ❑ *(1) Limited free support*: The group that created the viewer offers limited free support and instructions on viewer capabilities.
Picture Support	7	❑ *(10) Picture support*: The viewer supports the ability to spawn an additional window which contains 2D bitmap information. The picture file information is associated with an object or an action in the environment.
Text Support	7	❑ *(10) Text support*: The viewer supports the ability to spawn an additional window which contains text information. The text information is associated with an object or an action in the environment.
Text Support in Environment	7	❑ *(4) Text*: The viewer can display text in the simulated environment. ❑ *(2) Size*: The text's size can be displayed in the viewer. ❑ *Font*: The text's font can be displayed in the viewer. ❑ *Justification*: The text's justification can be displayed in the viewer. ❑ *Orientation*: The text's orientation can be displayed in the viewer. ❑ *(1) Color*: The text's color can be displayed in the viewer.
Line Support	7	❑ *(7) Line*: The viewer can display the lines in the environment. ❑ *(2) Pattern*: The viewer can display patterns on lines. ❑ *(1) Thickness*: The viewer can display the thickness of lines.
Undo Feature	7	❑ *(6) Multiple*: The viewer can step back though more than one action ❑ *(4) Single*: The viewer can step back a single action.
Load Time Speed	7	❑ *(10/X) Test number X*: The viewer can set up and load in the test case environments. A set of limits that represent the times that the viewer can do these tasks will be created. Load time of less than 1 minute is acceptable.
Transparency Support	6	❑ *(7) Transparency*: The viewer allows primitives to be partially or totally transparent when drawn in the environment. ❑ *(2) Adjust*: Transparency levels of primitives can be adjusted in the viewer. ❑ *(1) Turn on/off*: Transparency levels of the primitives can be turned on or off. If the adjust feature is marked, this feature is automatically marked.
Shading Support	6	❑ *(4) Interpolation*: The viewer allows primitives to be shaded by normal or intensity interpolation methods. ❑ *(3) Radiosity*: The viewer allows primitives to be shaded by radiosity methods. ❑ *(2) Flat*: The viewer allows primitives to be shaded by flat shading methods.
User Friendly	6	❑ *(10) User Friendly*: The viewer is ranked as either 'friendly' or 'not friendly' by a user who is not familiar with the viewer. The user will be run through a set of test cases.
Multiple Simultaneous Views	6	❑ *(4) Two or more views*: Two or more views of the environment can be shown simultaneously by the viewer. ❑ *(3) Three or more views*: Three or more views of the environment can be shown simultaneously by the viewer. ❑ *(2) Four or more views*: Four or more views of the environment can be shown simultaneously by the viewer. ❑ *(1) Five or more views*: Five or more views of the environment can be shown simultaneously by the viewer.

Criteria	Wt.	Sub Criteria
Color Support	6	❑ *(6) 16-bit or greater color*: The viewer can show a view of the environment in 16-bit (65536 colors) or a larger number of colors. ❑ *(3) 8-bit color*: The view can show a view of the environment in 8-bit color (256 colors). ❑ *(1) 4-bit color*: The viewer can show a view of the environment in 4-bit color (16 colors).
Mathematical Primitive Support	6	❑ *(3) Common 3D objects*: The viewer can display spheres or boxes. ❑ *(2) Less common 3D objects*: The viewer can display torii, or discs, or cylinders, or cones, or surfaces of revolution, or extruded surfaces. ❑ *(2) Common 2D objects*: The viewer can display ellipses or n-sided figures. ❑ *Less common 2D objects*: The viewer can display splines or arcs. ❑ *Rare 3D objects*: The viewer can display fractals or mathematical surfaces. ❑ *(1) Constructive Solid Geometry*: The viewer can display objects created out of logical operations (such as AND, OR) on a set of mathematical objects.
Measurement Units	6	❑ *(4) Options*: The viewer can convert a primitive's units of measure from one system to another. ❑ *(2) Units of Measure*: The view can display a primitive's units of measure. ❑ *(2) Dimensions*: The viewer can display a primitive's units dimensions. ❑ *(2) Turn on/off*: The viewer allows the user to turn the display of measurement units on and off.
Texture Support	5	❑ *(6) 2D Textures*: The viewer can support the display of two-dimensional textures on the surface of a primitive. ❑ *(3) Draw style*: The viewer can support the display of a particular repetitive pattern on the surface of a primitive. If a viewer has 2D textures, it has this sub-criterion. ❑ *(1) 3D Textures*: The viewer can support the display of three-dimensional textures on the surface primitive.
Animation	5	❑ *(4) 3D Transformation*: The viewer can support the display of an animation sequence, which is created by changing the transformation parameters of primitives. ❑ *(4) 3D Switches*: The viewer can support an animation display ❑ *2D Animation*: The viewer can support the display of an animation sequence, which is created by sequencing through a series of texture maps or material property patterns. ❑ *(1) 3D Morphing*: The viewer can support the display of an animation sequence, which is created by interpolating between different versions of a primitive's geometry.
Error Checking	5	❑ *(5) Corrupt files*: The viewer will give a meaningful error or warning message when reading in corrupt files. ❑ *(5) File versions*: The viewer will give a meaningful error or warning message when reading in files of a different version than the viewer supports.
Multiple File Load	4	❑ *(10) Multiple file load*: The viewer can load two or more un-nested, independent files into the same environment.
Slices/ Clip Planes	4	❑ *(5) Clip planes*: Additional clipping planes (other that the hither and yon planes) are supported in the viewer. ❑ *(4) Options*: The position of the clip plane can be modified in the viewer. ❑ *(1) Turn on/off*: The clip planes can be turned on or off in the viewer.
Render Order	4	❑ *(5) File format implementation*: The 3D viewer can render a set of primitives in the order specified by the file format. ❑ *(5) User implementation*: The 3D viewer can render a set of primitives in the order specified by the user.

Criteria	Wt.	Sub Criteria
Wireframe Support	3	❑ *(5) Wireframe*: The viewer supports the displaying of the environment as a set of wireframe surfaces. ❑ *(2) Depth cueing*: The wireframe lines are shaded in some way to indicate depth. ❑ *(2) Pattern*: The viewer allows adjustment of the patterns on wireframe lines. ❑ *(1) Thickness*: The viewer allows adjustment of the thickness of wireframe lines.
Documentation	3	❑ *(4) Electronic copy*: Documentation with a computer search capability is available. ❑ *(4) Tutorials*: A tutorial of how to use the viewer is available. ❑ *(2) Hard Copy*: Documentation in printed format is available, or an option to print the electronic copy is available.
Cross-Platform	2	❑ *(10) Cross-Platform*: Viewer is available on multiple major platforms (UNIX, Windows, MacOS).
Ease of Installation and Upgrade	2	❑ *(5) Install program*: Some type of automatic installation program handles the 3D viewer installation. ❑ *(3) All components*: The viewer does not require additional separate software packages or libraries to work. ❑ *(2) Instruction set*: A detailed, step by step set of instructions exists for installing the 3D viewer.
Point Support	2	❑ *(6) Display*: The viewer can display points in the environment. ❑ *(4) Size*: The point sizes can be displayed in the environment.
Sound Support	2	❑ *(10) Sound Support*: The viewer can play digitized sound information. The sound file information is associated with an object or an action in the environment.
Light Sources	2	❑ *(4) Infinite light source*: The 3D viewer can display infinite light sources. ❑ *(4) Local light source*: The 3D viewer can display local light sources. ❑ *Spotlight light source*: The 3D viewer can display spotlight light sources. ❑ *(1) Material Properties*: The 3D viewer can support the display of all the material properties in the file format "Material Properties" category.
File Compression Support	1	❑ *(10) Compressed files*: The viewer can read in 3D data files, which have had their data compressed.
Efficiency Issues with Large 3D Models	1	❑ *(10) Efficiency Issues*: The viewer implements some sort of efficiency scheme for handling large 3D models, such as LOD, or bounding or culling.

3D Viewers Evaluation Results

A two-pass process was used to evaluate the identified 3D viewers. During the first pass, each of the viewers identified in Table 5 was evaluated against a subset of the evaluation criteria found in Table 6. The evaluation criterion used during the first-pass evaluation are identified by bold type in Table 6. These "first-pass" criteria were chosen by their relatively high weight as well as the short amount of time it took to determine their answer. During the second pass, *all* of the evaluation criteria from Table 6 were used to score the viewer.

The primary reason for the first-pass evaluation was to determine which of the 19 viewers should be fully evaluated. Due to the duration and dollar value of the effort, all of the 19 viewers could not be fully evaluated. The first-pass evaluation process took, on average, a hour to complete. The second-pass evaluation process for each viewer took an average of six hours – although the time was reduced to two hours for VRML viewers once a test bed of VRML files was established. Table 7 summarizes the results of the first-pass evaluation. The first column of the table identifies the evaluated viewer and the second column contains the normalized (0-100) score.

Table 7. First Pass Evaluation Results

Viewer	Normalized Score
Cosmo Player v2.1 Beta	71
3D Studio Max 1.2	70.3
Realiview / Realimation 4.3	64.7
Community Client 3D 3.02	64.0
Platinum WIRL 1.0 Beta G	60.3
World View 2.0	58.5
Community Place VRML 2.0 D2	54.4
V-Realm Browser 1.1 Build 1	54.1
ActiveCGM Browser 5.0	48.5
ConceptCAD 3.1 TestDrive	46.5
Quicktime VR 2.1.2	40.8
OZ Virtual 2.0b3	39.2
World Up Player Release 4	38.5
3D View 2.1	34.0
3Dspace Assistant 2.0 Template	33.1
Virtus Player 3.0	30.4
NetAnimator 1.0 Release 3	27.5
Beyond 3D Extreme 2.01 beta	26.3
Cult3D 1.1	26.0
Quick3D Beta	19.2

Based on the results of the first-pass evaluation results, six viewers were selected for the full review. The four highest ranking viewers (Cosmo Player, 3D Studio Max, Realiview / Realimation, Community Client 3D) were chosen to find the best product to use in the study. Two medium-to-lower ranking viewers (V-Realm Browser, OZ Virtual) were chosen to validate

whether or not conducting a first-pass test would indicate (roughly) the score of a final test. As shown from the scores in the first-pass and final evaluation scores, viewers that rank highly in the preliminary scoring system tend to score highly in the final scoring system; low preliminary scorers tend to score low in the final scoring system.

Table 8 summarizes how the six selected viewers performed against the full set of evaluation criteria. The six viewers are listed across the top of the table starting in the second column. The first column identifies the criterion. The raw score for each of the criteria is provided starting in the second column and second row, where the raw score is defined to be the sum of the satisfied sub-criteria times the weight for the particular criterion. The last two rows of Table 8 list the raw score total and the normalized score for each of the file formats. The raw score total was calculated by adding all of the raw scores for each of the criterion. Dividing the raw score by the total possible points, in this case 2180, produced a normalized score for each of the file formats (a score between 0-100).

Table 8. 3D Viewer Evaluation Results

	3D Studio Max v1.2	Cosmo Player v2.1 Beta	Community Client 3-D 3.0	Realiview/ Realimation 4.3	OZ Virtual 2.0b3	V-Realm Browser 1.1
Cost	0	100	100	100	100	100
Perspective View	70	70	70	100	70	70
Stability/ Robustness	100	100	100	100	80	0
Extensibility	100	50	50	0	0	0
Groupings	100	60	60	50	20	30
Polygon Support	90	90	90	90	90	90
Run Time Speed	80	80	80	80	64	0
WWW Plug-In	0	64	64	80	80	80
Orthogonal View	63	0	0	70	0	0
Software Support	70	70	56	49	56	0
Picture Support	0	70	70	70	0	70
Text Support	70	70	70	70	0	0
Text Support in Environment	63	70	63	56	0	63
Line Support	49	49	49	0	0	0
Undo Feature	70	70	0	0	0	0
Load Time Speed	70	70	70	70	56	0
Transparency Support	60	42	42	42	42	0
Shading Support	42	24	42	36	42	42
User Friendly	60	60	60	60	60	0
Multiple Simultaneous Views	54	0	0	0	0	0
Color Support	60	60	24	60	60	60
Mathematical Primitive Support	54	30	30	30	30	30
Measurement Units	36	0	0	0	0	0
Texture Support	45	45	45	45	45	45
Animation	50	50	45	20	0	0
Error Checking	0	50	0	0	50	25
Multiple File Load	40	0	0	0	0	0
Slices/ Clip Planes	0	0	0	0	0	0
Render Order	0	0	0	0	0	0
Wireframe Support	21	0	15	15	0	15
Documentation	30	30	18	18	0	0
Cross-Platform	0	20	0	0	0	0
Ease of Installation and Upgrade	20	20	20	20	20	20
Point Support	12	12	12	0	0	0
Sound Support	0	20	20	0	20	0
Light Sources	18	20	20	20	18	0
File Compression Support	0	10	10	0	0	10
Efficiency Issues with Large 3D models	10	10	10	10	10	10
Raw Score Total	1607	1586	1405	1361	1013	760
Normalized Score (0-100)	73.7	72.8	64.4	62.4	46.5	34.9

Descriptions of 3D Viewers

3D Studio MAX 1.2, 73.7%

3D Studio MAX is a software package developed and sold by Kinetix, a division of Autodesk Inc. This package has roots in the computer-aided design market, and retains many of the features of CAD software, but has been expanded to accommodate the needs of computer animators. 3D Studio MAX is geared to the expert user, and its user-interface can be rather daunting to a novice, but it has many features useful for an aircraft maintenance task, and can be extended via third-party plug-ins.

The main strengths of 3D Studio MAX are its support for polygons, named object groupings, multiple independent views, orthogonal views, measurement units, numerous mathematical object types, and its extensibility. It faltered somewhat on links to external text, since its support was limited to a single window of unformatted text that had to be input via 3D Studio MAX, rather than linking to an existing file. Other drawbacks included a high price tag, an inability to associate a 2D picture with an object or action, and an inability to be run as a plug-in a WWW browser.

Cosmo Player 2.1, 72.8%

Cosmo Player 2.1 is a free, high-performance, cross-platform viewer for applications written in VRML 2.0, the open standard for 3D content on the Web. Cosmo Player was developed by Silicon Graphics, Inc. (SGI) to be fully compliant with VRML 2.0 specifications, plus to take full advantage of popular user-side graphics "turbocharging" such as Direct3D, OpenGL, and AGP technology. The viewer interface is easy on beginners yet full featured for experts.

With its user friendliness and powerful features, the viewer has become very popular, with millions of free versions distributed to date. For users with PC compatibles, the viewer is a plug-in for Communicator 4.x, and ActiveX control for Internet Explorer 4.X.

Although Cosmo Player is a widely-used VRML viewer, it has a few shortcomings. It is not capable of displaying objects in an orthogonal view, supports only one view of a scene, does not support measurement units, and does not support displaying objects in a wireframe view.

Blaxxun Community Client 3D, 64.4%

Community Client 3D (CC3D) is a VRML viewer distributed by Blaxxun Interactive. Blaxxun targets their Community Client family of products to the on-line community. (Their more advanced product, CCpro, adds a number of multi-user environment features to the features available in CC3D.)

CC3D is a plug-in for the Explorer and Communicator Web browsers. CC3D correctly reads in files in VRML 2.0. It fully supports polygons, text and picture links and almost all of the embedded text features, as well as light sources, sounds, compressed files and LOD, groupings, shading, textures and animations. It supports the basic features of lines, transparency, mathematical objects, wireframe. and points. The CC3D viewer does not support an undo feature, multiple simultaneous views, measurement units, error checking, multiple file loads, orthogonal views, or arbitrary clip planes.

Realiview / RealiMation 4.3, 62.4%

Realiview is a free viewer distributed by RealiMation, Inc. RealiMation is also the name given to a suite of products for visualization, simulation and games. The RealiMation Space Time Editor (STE) must be used to create the Realibases that can be read and displayed by Realiview. The latest version of the RealiMation product line is version 4.3.

Realiview is available as both a stand-alone package or as a plug-in to a Web browser. Realiview will run on either a Windows 95 or Windows NT workstation. The interfaces for the stand-alone and the plug-in, although slightly different, are fairly easy to use.

Realiview offers full support of both perspective and orthogonal viewing. It supports links to external pictures and text as well as embedded text in the environment. It supports full color and lighting and basic shading and 2D textures. For a number of features, Realiview

provides basic support, but it does not support the more complex elements. Some of these features include groupings, animations, mathematical objects, and wireframe.

Realiview supports only a single simultaneous view, although it is fairly easy to switch between a number of pre-set views. Realiview does not allow extensibility by either the user or third-party vendors, and it does not support an undo feature, measurement units, multiple file loads, arbitrary clip planes, render order information, lines, or points.

OZ Virtual 2.0 b3, 46.5%

OZ Virtual 2.0 was developed by OZ Interactive. OZ Virtual allows a user to navigate a 3D world and to create a totally interactive, multi-user environment, which allows the user to communicate with people throughout the world. From the startup 3D world one can navigate to other worlds by double-clicking hot-spots, or open any other 3D world represented by a VRML file.

The strengths of OZ Virtual are the ability to run both stand-alone and as a plug-in. It will render VRML files, and the viewer is free. However, OZ Virtual has many shortcomings. It is only partially VRML 2.0 compliant, has limited support for manipulating groups of objects, and has no support for an orthogonal views, text, or line support. It supports only one view and does not support rendering objects in wireframe. The viewer also is somewhat difficult to use to navigate 3D scenes.

V-Realm 1.1, 34.9%

The V-Realm viewer is a VRML viewer produced by Integrated Data Systems (IDS). V-Realm products have been transferred to the Ligos Corporation, a subsidiary of IDS. They no longer appear to support this viewer , but they do sell V-Realm Builder, a package for creating VRML worlds. Several tests were not completed due to the discontinuation of this viewer.

The V-Realm viewer is available as a stand-alone and a plug-in product to a Web browser. The viewer supports only Version 1.0 of the VRML specification. The viewer allows links to pictures and text as well as text in the environment. It fully supports the polygon criteria, color criteria, and most of the features of shading and textures. Additionally, it was able to

handle compressed files and supports LOD, limited features of perspective view, groupings, mathematical objects and wireframe.

It does not support orthogonal viewing, lines, the undo feature, transparency, multiple simultaneous views, measurement units, animation, multiple file loads, arbitrary clip planes, points, or light sources.

3D MODEL CREATION

Model Creation Process

In support of the comparative study, a 3D model of an F-15 aircraft, including a detailed model of bay 3R, was required. An initial search to find a complete model of an F-15, complete with all internal parts, Line Replaceable Units (LRUs), and structural elements was conducted. Although several labs claimed to have such a model, or parts of one, most would not or could not (due to classification) release the data. As a result, the focus of the effort turned to creating suitable models.

Due to its large user base, number of features, and support, the tool chosen for the modeling effort was 3D Studio Max v1.2. The modeling effort was divided into five sections:

1) Finding and converting an outer shell of an F-15 model to a file format that would be usable by 3D Studio Max.
2) Create the shelves and LRUs of bay 3R.
3) Combine the models from steps 1 and 2 to create a single F-15 model.
4) Add animation and VRML triggers to the F-15 model.
5) Converting the F-15 model to MAX/VRML formats.

Identifying and Converting F-15 Outer Shell

The DEPTH (Design Evaluation for Personnel, Training, and Human Factors) laboratory, at Wright Patterson AFB, Dayton, OH, provided a model of an F-15 which had previously been used for several studies involving simulation of maintenance activity. The model contained a realistic outer shell of an F-15 with the 3R bay already marked, and was ideal for the purposes of this project.

However, this model was being used in the DEPTH lab under Transom Jack, a human-centric visual simulator. In order to use the F-15 model for this project, it needed to be converted from Transom Jack's internal format into a format suitable for the project's modeler program, 3D Studio Max. At the time, there were no converters capable of a direct conversion from the Transom Jack file format to the 3D Studio Max file format.

By using several different converters in conjunction with one another, the ability to convert files from Transom Jack to 3D Studio Max was created. By converting from Transom Jack's format to VRML 1.0 to AutoCAD's DXF and finally to Kinetix's MAX file format, the model data was loaded into 3D Studio Max. A discussion of this process follows.

1) Convert Transom Jack's native format to VRML 1.0:

The DEPTH lab's version of Transom Jack contained a plug-in module which allowed any model in Transom Jack to be exported directly into a VRML 1.0 file. However, using the plug-in produced VRML 1.0 files with several syntax errors, all of which were easily fixed by editing the file with a text editor. The conversion was completed on a Silicon Graphics Onyx computer.

2) Convert VRML 1.0 into DXF:

It should be noted that many converters exist to convert a format *to* VRML 1.0, but there are very few which converted *from* VRML 1.0 to another 3D file format. After much searching, a freeware converter named Crossroads (a 1.0 beta, created by Keith Rule) was found. It could read in the VRML 1.0 F-15 model on a Pentium 200 Windows NT system and converted to a DXF file with no visible errors.

3) Convert DXF to 3D Studio Max's internal format:

Kinetix, the creator of 3D Studio Max, offered a free plug-in which read DXF files into 3D Studio Max. The conversion took several hours of solid CPU time to convert the data from DXF to MAX using a Pentium 200 MHz under Windows NT.

One problem with this method of successive conversions is that information can be lost between each transfer. For example, VRML 1.0 can handle some limited forms of animation in its format, and AutoCAD's DXF cannot. Therefore, any conversion of VRML 1.0 to DXF will result in a model without animation characteristics. If this process were to be extended (for example, VRML 1.0 -> DXF -> POV -> OBJ -> FLT), more and more characteristics would be lost between the original format and the final format due to the differing function sets of each of the formats.

There was also the issue of poor converters - very few converters actually convert the entire feature sets of the 3D file formats. Although both VRML 1.0 and DXF can store models as a hierarchy of objects, there was no guarantee that a particular converter will actually process the hierarchy feature. Implementations of these converters vary greatly, and the difference between a good converter and a poor one is often whether or not a description of what features it could and could not handle is included.

Neither of these problems presented a serious barrier to the modeling effort, since all that was needed was the set of polygonal geometry representing the F-15's outer hull, and all converters that were used processed this feature.

Figure 5 shows the F-15 shell which was converted and eventually imported into 3D Studio Max.

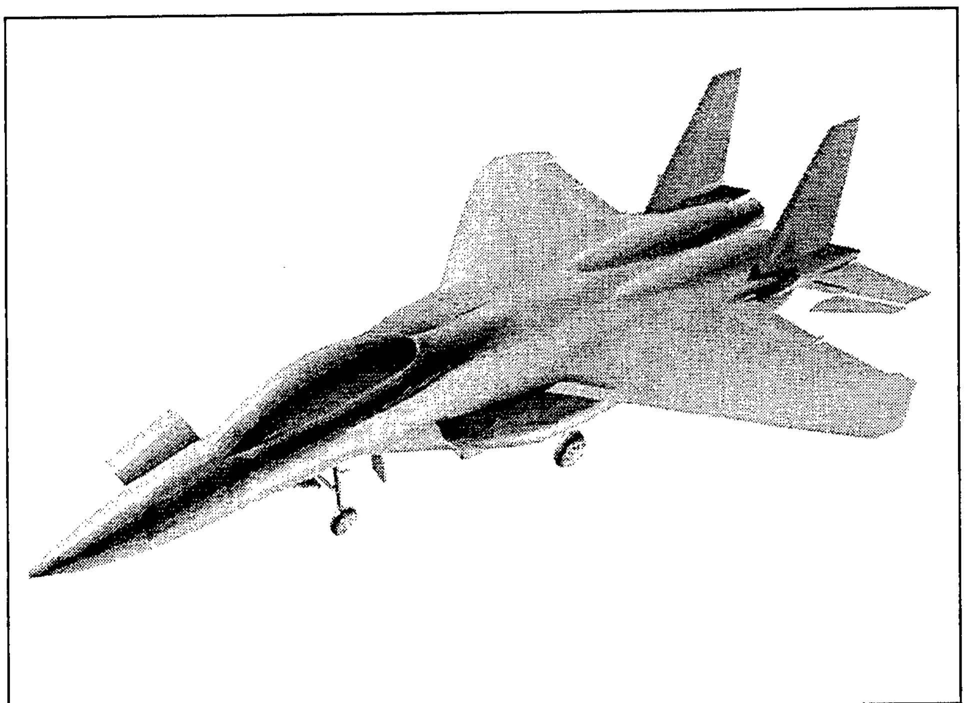


Figure 5. 3D Studio Max Rendering of F-15 Shell.

Creating Shelf Assembly and LRUs of Bay 3R

The 1F-15A-39 ABDR TO was used extensively to create the shelf assembly of bay 3R. It should be noted that although the TO was used to build a virtual F-15 in this project, it was

never intended for this purpose. Consequently, many measurement calculations for various components were not included in the TO, thus requiring the software team to estimate measurements directly from orthogonal view diagrams. These measurements were then used to model the 3D objects representing the shelves, centerline plenum, and several of the miscellaneous features such as wire holes and ribbings on the shelves. The models were fairly simple, and required only setting basic color and lighting components similar to the real-life shelves. All colors chosen (generally a metallic green-blue for the shelves) were based on the colors found in a real F-15.

Although the TO contained detailed information on the behavior of damaged LRUs and a single black and white drawing of the 3R bay, more information was required to accurately model the LRUs for the 3D model. To obtain this information, F-15 3R bays were photographed at the Air Force Museum at Wright-Patterson AFB and the 653 CLSS at Robins AFB.

These photos provided rough measurements of height and width for each LRU. Simulated objects representing the LRUs were modeled under 3D Studio Max. The models were slightly more complex than the shelves and included texture maps as well as some extra details. By editing the digital photographs with a 2D paint program (Paint Shop Pro 5.0), texture maps were created for the front faces of each of the LRUs. These texture maps were then applied to the 3D objects, and a reasonable facsimile of the LRUs was created. Figure 6 shows the model of bay 3R. Care was taken to ensure that the final texture maps kept the same color scheme as the original items.

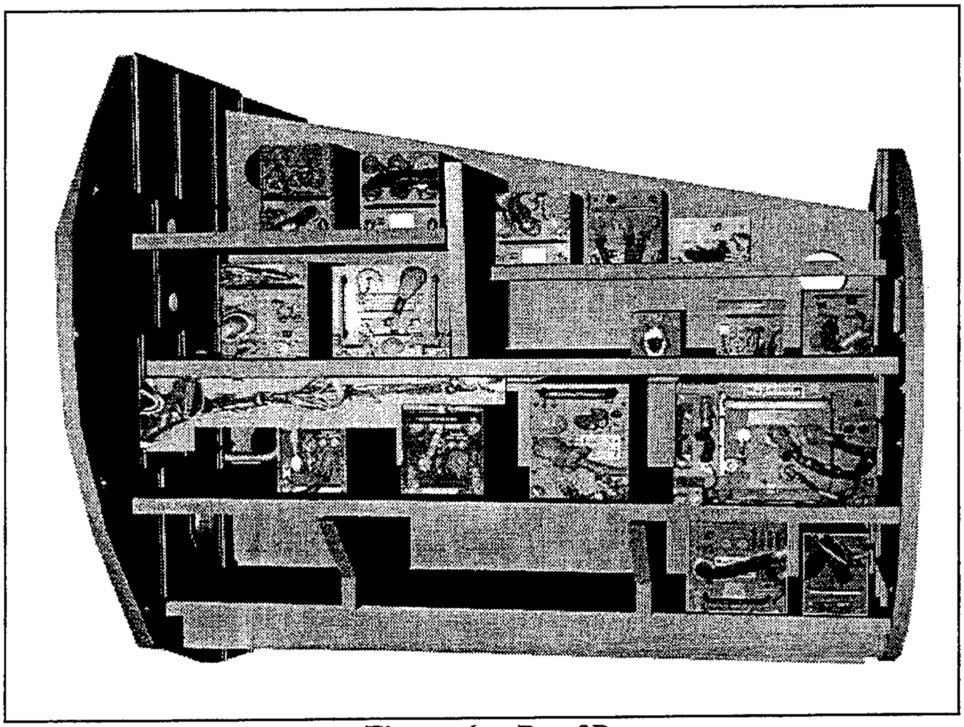


Figure 6. Bay 3R.

Combining the F-15 Shell and Bay 3R

Once both models were created, it was necessary to combine the F-15 shell and the LRU models/shelves to create a single model. Despite the (often) rough measurements used to create the bay 3R shelves, the entire shelf assembly fit into the F-15 shell provided by the DEPTH lab with minor sizing modifications.

Some optimization of the combined model was performed at this stage to improve the frame rate. Several surfaces, especially parts of the F-15 shell, contained far more detail than was needed for the project. As a result, these parts, including the landing gear and engine nozzle sections, had their total number of polygons reduced by nearly one-third to increase the frame rate. Several minor flaws in the model, such as polygons with reversed backfacing, were also cleaned up during this stage. Figure 7 shows the results of combining the F-15 shell with Bay 3R.

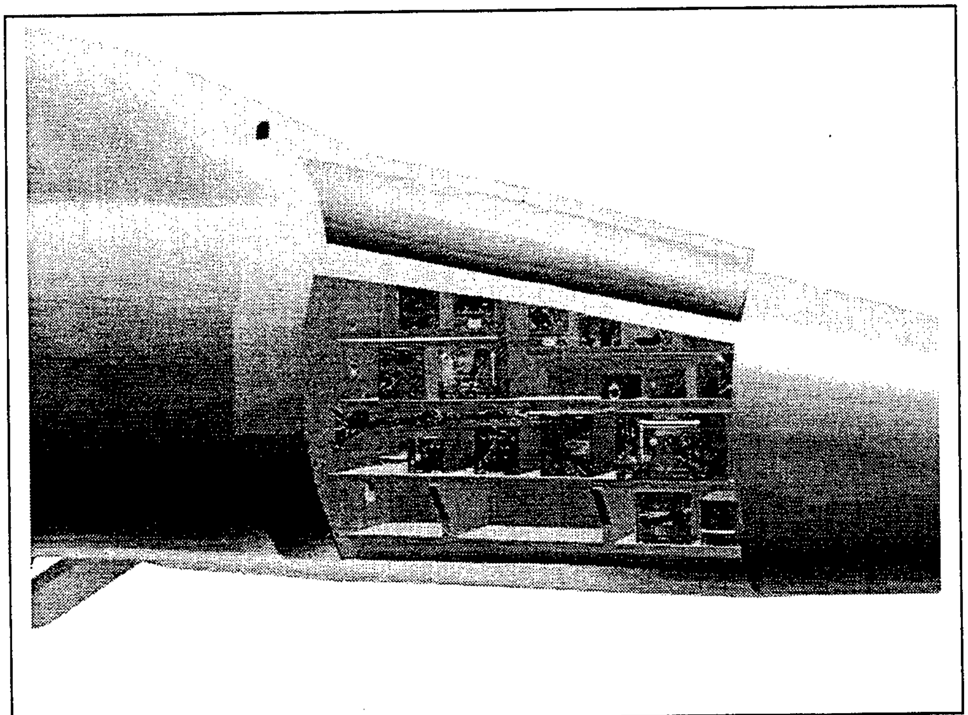


Figure 7. Complete F15 Model.

Creating Animation and Triggers

A small three-button panel was created under each LRU in the model. VRML 2.0 TouchSensor and TimeSensor triggers were added to each button in the panel. These triggers, when used in conjunction with animation capabilities, allowed the user to change whether or not a LRU was displayed on-screen and with or without textual information.

This (label) textural information was created to help in the identification and location of components within a graphic. System assessment/repair text from the Automatic Flight Control

System, Communication, and Navigation Systems of the 1F-15A-39 ABDR TO was converted into a set of HTML files. By linking TouchSensor triggers to the HTML documents, the ability to spawn additional browser windows containing this textural information was created. It should be noted that adding the VRML triggers and HTML files only produced these extra capabilities in a VRML simulation, specifically, Cosmo Player. For the 3D Studio Max simulation, equivalent functionalities were found in Max's features – specifically, the onscreen display/ hiding capability was created with the Unhide / Hide By Name feature, and the display information capability was created by adding system assessment text into a spawnable Properties window.

Finally, the models were exported from 3D Studio Max's internal format to VRML 2.0 for use in the VRML browsers. The original MAX file was used during the review of 3D Studio Max as a 3D viewer.

Converting the F-15 Model to MAX/VRML Formats

Based on the evaluation results of the 3D viewers, Cosmo Player and 3D Studio Max were selected for use in the execution of the comparative study. The required file formats for Cosmo Player and 3D Studio Max are VRML 2.0 and MAX, respectively. Since the model was created using 3D Studio Max, it was automatically available in the MAX file format. The export feature of 3D Studio was used to produce a VRML 2.0 version of the model

Cost of Model Creation

Table 9 summarizes the time and cost for developing the above described F15 model. The table breaks up the creation and development of the model into five main tasks. Associated with each of the tasks is the time required to complete the tasks. Finally, to compute the cost associated with each task a labor rate of $65.49 an hour was used. This labor rate is based on TASC's GSA ADP labor rate for a software developer with two years experience.

Table 9. Cost of Model Creation

Task	Time	Cost
Identify and Converting F-15 Model	32 hours	$2,096
Model Shelves, centerline plenum, and LRUs	38 hours	$2,489
Create and add texture maps to LRUs	21 hours	$1,375
Combine shelves and LRUs in F-15 shell	5 hours	$327
Develop VRML animation	32 hours	$2,096
Totals	**128 hours**	**$8,383**

COMPARATIVE STUDY

Method

A comparative study was conducted on the use of 3D graphics in F-15 maintenance. This portion of the project focused on the direct application of a 3D model for use in a particular maintenance task. The findings from the CTA were used to help design a 3D graphic (model) of bay 3R of the F-15. Two viewers, Cosmo Player, from here on referred to as Cosmo, and 3D Studio Max, were used to display and manipulate the 3D model.

Subjects

Six maintainers participated in the comparative study. None of these maintainers participated in the CTA. All had ABDR maintenance experience. They also had an average of seven years computer experience. Three had experience with 3D graphics, but none had any familiarity with the test bed viewing applications.

Procedure

Before starting, the maintainers were briefed on the background and goals of this portion of the project. After the briefing, the maintainers completed a background information questionnaire (Appendix D). They were then given only one of the two viewers to evaluate. Maintainers that participated the first day of data collection evaluated the Cosmo viewer while the second day's maintainers used 3D Studio Max. Each maintainer was given a choice of input device: an external mouse or an integrated pointing stick controller located on the keyboard. Because of the maintainers' familiarity with the external mouse, all selected this means of control.

Since the maintainers were not familiar with either viewer, they were given extensive instructions. The maintainers were first shown all of the available features in the particular viewer. After this, they were instructed to perform several tasks that utilized each of these features. Once the maintainers and the experimenter felt confident that the task could be completed, training was terminated.

The main study focused on an F-15 aircraft. The aircraft used was located in a hanger at Robins AFB. A table and laptop computer were placed at the nose end of the plane. The 3D model and viewers were run on a Pentium 233 MHz laptop PC with a screen size of 13.3 inches.

The display signal from the laptop was repeated on an additional monitor, which allowed researchers the opportunity to watch and videotape the use of the model and viewer. The post-task questionnaire presented to the maintainers was audiotaped for use in analysis. The questionnaire asked a series of probing questions to gather information on the 3D model and viewer (Appendix E).

To start the task, the maintainers were given a hypothetical scenario describing the damage sustained by the aircraft. They were asked to identify all of the aircraft damage, signified by white stickers placed on the aircraft, and to mark it on the 3D-computer model. There were a total of nine damage locations. The order in which the maintainers located and marked the damage on the model was unrestricted. All of the maintainers alternated between the aircraft and the 3D model to correctly identify all nine locations of damage. A copy of the protocol for the comparative study can be found in Appendix F.

Viewers

Cosmo Player 2.1

The Cosmo Player version 2.1 (Cosmo) is a Web browser plug-in which extends the functionality of both Netscape's Communicator 4.x version and Microsoft's Internet Explorer 4.x version browsers. For this study, Netscape's Communicator version 4.04 was used. The Cosmo plug-in provides a viewer for 3D models authored in the VRML. A dashboard of controls at the bottom of the screen is provided in Cosmo for manipulating the 3D model. In this study, only a subset of the available controls was made available to the maintainers: zoom, rotate, pan, tilt, go, slide, seek, straighten, and undo/redo. Three other capabilities which were not built in features of Cosmo were also available to the maintainers: information, remove/replace, and mark. It should be noted that all of the controls available in Cosmo can be executed using the keyboard, but for this study, the maintainers were instructed to use the pointing device. A short description of each of these controls follows.

Cosmo Player 2.1 Features:

ZOOM. Allows the user to increase or decrease the effective size of the 3D model.

ROTATE. Allows the user to spin (rotate) the 3D model about any axis. The axis of rotation is determined by the direction the user drags the mouse. For example, if the user drags the mouse horizontally left to right directions, the model will be rotated around the vertical axis in a left to right direction. Similarly, if the user drags the mouse in a vertical direction, the model will be rotated around the horizontal axis. Other angles of rotation can be accomplished by dragging the mouse in an angular direction.

PAN. Allows the user to move the model left, right, up, or down. Dragging the mouse to the left moves the model to the left, etc. The speed at which the model moves using the "pan" feature is constant.

GO. Allows the user to move in any direction on the screen. This feature turns the user's point of view in the direction of the movement. Dragging up moves the user's view closer, dragging down moves the user's view outward, dragging left or right moves the user's view to the left or right.

SLIDE. Like "pan", the "slide" feature allows the user to move the model left, right, up, or down. The main difference between the "slide" and "pan" features is that the speed at which the model moves can be controlled using the "slide" feature while it is fixed with the "pan" feature. The slide feature does not turn the user's point of view (as does the Go feature); it simply moves the model in the desired direction (the user's point of view is fixed).

TILT. Allows the user's point of view to be tilted. This can be thought as tilting a camera along a fixed axis of rotation. The "tilt" feature will not allow the user to turn the view upside down.

SEEK. Allows the user quick navigation to an area within the 3D model. Once the seek button is selected, the user places the cursor on an area of interest and clicks the left mouse button. Cosmo will then position the user's point of view at the area of interest.

STRAIGHTEN. Returns the user's point of view to a straight and level position.

UNDO/REDO. Cosmo maintains a history of moves that the user has executed. The "undo" feature allows the user to undo the last operation executed. The "undo" feature can be used in succession to undo the last several operations. "Redo" allows the user to repeat the last operation executed.

Custom Features:

INFORMATION. The information feature allowed the user to access textual information associated with a particular LRU. This feature was implemented by utilizing Touch Sensors in the VRML language, which provided the ability to set up "hot spots" in the 3D model. Associated with these "hot spots" was an event that loaded an HTML page containing information about the selected LRU.

REMOVE/REPLACE. Again using "hot spots," the ability to remove and replace objects in the 3D model was developed. Each of the LRUs in the model had three associated buttons (remove, replace, and information) which when selected with the mouse would remove the object (if not already removed) or replace the object (if already removed).

MARK. The "mark" feature provided the maintainer with the ability to mark the simulated damage on the 3D model. A screen capture program called HyperSnap-DX Pro was used to implement the "mark" feature. To mark a damage spot on the model, the maintainer placed the cursor at the desired location and selected a defined essential combination. Which triggered the HyperSnap application to execute a screen capture, which recorded the cursor location at the damaged spot on the screen and associated with the aircraft.

3D Studio Max 1.2

The other viewer used in the study was a 3D modeling package called 3D Studio Max. As opposed to the plug-in Cosmo, 3D Studio Max is a standalone package designed for creating and viewing 3D models. 3D Studio Max provides for many different possibilities to view a model. In this study, the team used a single, fully rendered perspective view. This view was analogous to the view provided in Cosmo. Because it is used primarily as a design tool (as opposed to being strictly a viewer), 3D Studio Max contains many controls and features. In order to reduce complexity, the maintainers used only a small subset of the available features: zoom, pan, seek, rotate remove/replace, and undo/redo. Additional features demonstrated to but not

used by the maintainers. These included multiple simultaneous views, measurement units, and wire frame view. A brief explanation of each of the features is provided below.

3D Studio Max Features Used by Maintainers:

ZOOM. Allows the user to increase or decrease the effective size of the model.

PAN: Allows the user to move the model left, right, up, or down. Dragging the mouse to the left moves the model to the right, dragging the mouse to the right moves the model to the left, etc.

SEEK. A two step process had to be followed to achieve seek feature. The first step consisted of selecting the desired object. After selecting an object, the user then selected the "zoom extents" command, which zoomed the viewer on the selected object.

ROTATE. Allows the user to rotate the model along any axis. As with Cosmo, the direction in which the user drags the mouse determines the angle of rotation. Another aspect of the "rotate" feature in 3D Studio Max is the ability to constrain the axis of rotation along the horizontal (typically the x-axis) or the vertical axis (typically the z-axis).

REMOVE/REPLACE. Like the seek feature in 3D Studio Max, the "remove/replace" feature required a two step process. To remove an object, the first step was to select the object. To complete the procedure, the "hide selected" option was chosen and the object was removed. For the "replace" feature, the object was selected by name from a list of hidden objects. The "unhide selected" option was chosen and the object reappeared in the model.

UNDO/REDO. This feature was identical to the "undo/redo" feature found in Cosmo.

3D Studio Max Features Demonstrated to Maintainers:

Multiple simultaneous views. The "multiple simultaneous views" feature found in 3D Studio Max allows the user to have up to four different views of the model on the screen at one time. For example, a top, front, side, and perspective view can all be shown.

Measurement units. 3D Studio Max allows the user to set up measurement units for a model. Once the measurement units have been established and entered by the user, the user can determine the x,y,z coordinates of the mouse relative on the measurement units supplied.

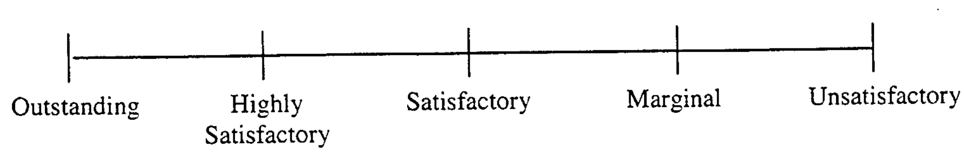
Wireframe view. 3D Studio Max can be configured so that the program switches to a wireframe mode when the model is being manipulated (rotated, zoomed, etc.). This has the advantage of providing a much faster frame rate (update speed) than under normal conditions.

Data Analysis

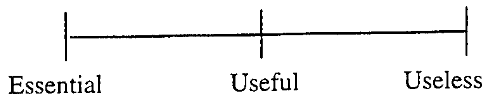
The raw data consisted of the research team's notes, audio recordings of the prebriefing and postbriefing, video recordings of the scenario execution, and the results of the questionnaires. The answers from the questionnaire are summarized below. After a series of general questions, two questions were asked about each of the operations available in the viewers. A table was created for each feature to summarize the maintainers' responses. An example of one of the tables is provided below. Columns one through five identify the subject, ease of use, number of operations, percentage of what an operation was used, and the operation's rating. The following section summarizes the subjects' answers for each of the questions in the questionnaire. (Note: Some of the maintainers that used the Cosmo viewer used the straighten feature, which was not addressed in the questionnaire.)

Viewer: Cosmo		**Operation: Zoom**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	1	2%	Useful
Subject 2	Highly Satisfactory	8	13%	Useful
Subject 3	Highly Satisfactory	1	2%	Essential

Two sets of scales were used to evaluate the features. When asked to rank the ease of use for the features the maintainers were given a scale ranging between "Outstanding" and "Unsatisfactory" as seen below.



In some particular cases they were also asked to rate the necessity of the feature between "Essential" and "Useless" as seen below.



QUESTION: Were the 3D graphics easy to use?

All but one of the maintainers stated the 3D graphics were easy to use. The one maintainer who responded "No" commented that with sufficient practice the graphics would be easy to use.

QUESTION: Did the laptop computer hinder your ability to use the 3D graphics?

Four of the six maintainers responded that the laptop did not hinder their ability to use the 3D graphics. One of maintainers, who indicated that the laptop hindered his ability, also stated that the computer was slow. The same maintainer commented that even if the laptop was slow, maintainers would still use it. Another maintainer stated, "the ability to take the laptop to aircraft would be very beneficial because it would be easily accessible while doing an assessment".

Two issues were raised regarding the laptop's use in an operational environment. First, one subject expressed a concern about the survivability and reliability of a laptop computer at a deployed site. Environmental conditions can be extreme during a deployment, jeopardizing the laptop's reliability.

Second, the use of electronic devices near the fuel cells was also discussed. An electronic component may not be permitted when performing assessments near fuel cells, due to the possibility of igniting the vapors.

QUESTION: Adequacy of the screen size for displaying the 3D graphics.

All of the maintainers ranked the adequacy of the screen size as satisfactory or better with one of the maintainers ranking it "Outstanding." One of the maintainers mentioned that the larger the screen size the better.

QUESTION: Adequacy of the input device for manipulating the 3D graphics.

All of the maintainers ranked the adequacy of the input device to be between "Highly Satisfactory" and "Satisfactory." Three of the maintainers mentioned the possibility of using a trackball or joystick as an alternative input device. Another comment was made in regard to having to do assessments in full chemical gear including heavy rubber gloves. This maintainer said that it would be very difficult to use a pointing stick or touch pad (typical integrated input devices in laptop computers) while wearing the gloves.

QUESTION: Use of the laptop computer as a tool to manipulate the 3D graphics.

Five out of the six maintainers ranked the use of the laptop computer to manipulate the 3D graphics as "Highly Satisfactory" or above. The remaining maintainer gave a ranking between "Highly Satisfactory" to "Satisfactory" and commented that he would have preferred a faster laptop, which would have updated the graphics more quickly.

QUESTION: Were the 3D graphics displayed in this task realistic and reliable? Why?

Four of the maintainers stated that the graphics were realistic and reliable. Three of the maintainers commented that there needed to be more detail in the model if the system was ever to go into production. Two of the maintainers commented that more detail on the structure should be modeled. Another maintainer pointed out that the hose clamps that secured the coolant line to the center plenum were not modeled which caused him some problems in accurately identifying one of the damaged areas.

QUESTION: Realism of the 3D graphics.

Three of the maintainers commented that the realism of the graphics was outstanding and the remaining three gave a ranking between "Highly Satisfactory" to "Satisfactory." One of the maintainers commented, "It made you feel that you were actually on the aircraft."

QUESTION: Were there any misplaced or missing landmarks in the 3D graphics? If there were, did they cause problems in the scenario?

All six of the maintainers cited misplaced or missing landmarks in the model. Three of the maintainers mentioned missing details in the modeling of the structure. Some of the specific areas mentioned were the lightening holes were not modeled and there was a rib that connected two of the shelves that was missing. One maintainer recommended more detail be modeled on the structure. He said that the structure of the aircraft rarely changes. He also pointed out that in an ABDR assessment, if an LRU is determined to be damaged, it is removed and replaced with a new one. Because of this, there does not need to be a great deal of detail in modeling the LRUs.

Another maintainer pointed out that the hose clamps that attached the coolant line to the center plenum were missing and caused him difficulty in properly locating some of the damaged areas. This same maintainer mentioned that it would be helpful if the tubes were labeled as they are on the aircraft (high pressure, low pressure, etc.).

QUESTION: Could you please provide examples of additional manipulation features that would be helpful?

Five out of the six maintainers recommended additional manipulation features. One of the maintainers suggested providing the capabilities to enter coordinates and has the viewer position the model to the entered coordinates. The same maintainer also suggested allowing the user to enter an area of damage, for example bay 3R, and have the viewer position the model so that bay was visible.

Another suggestion was to use a trackball and directional buttons for navigation. This maintainer suggested providing controls similar to a video game for manipulating the model. The directional buttons would allow constrained manipulation along a single axis. Another suggestion was to use a touch screen to manipulate the image.

QUESTION: Please mark the features you used in the task just performed.

	Sub. 1	Sub. 2	Sub. 3	Sub. 4	Sub. 5	Sub. 6
Seek	X	X	X	X	X	X
Zoom	X	X	X	X	X	X
Rotate	X	X	X	X	X	X
Pan	X	X		X	X	X
Undo/Redo	X	X	X	X	X	X
Remove/Replace	X	X	X	X	X	X
Mark	X	X	X	X	X	X
Information	X		X			
Tilt	X	X	X			
Go	X	X	X			
Slide	X		X			

QUESTION: Ease in using the seek feature. Please rate the seek feature.

Viewer: Cosmo		**Feature: Seek**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Outstanding	4	6%	Essential
Subject 2	Outstanding	12	19%	Essential
Subject 3	Satisfactory	1	2%	Useful

3D Studio Max		**Feature: Seek**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 4	Satisfactory	4	8%	Essential
Subject 5	Outstanding	4	8%	Essential
Subject 6	Outstanding	4	6%	Useful

QUESTION: Ease in using the zoom feature. Please rate the zoom feature.

Viewer: Cosmo		**Feature: Zoom**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	1	2%	Useful
Subject 2	Highly Satisfactory	8	13%	Useful
Subject 3	Highly Satisfactory	1	2%	Essential

Viewer: 3D Studio Max		**Feature: Zoom**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 4	Marginal	9	17%	Essential
Subject 5	Highly Satisfactory	12	23%	Essential
Subject 6	Highly Satisfactory	13	21%	Essential

QUESTION: **Ease in using the rotate feature. Please rate the rotate feature.**

Viewer: Cosmo		**Feature: Rotate**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	7	11%	Useful
Subject 2	Highly Satisfactory	12	19%	Essential
Subject 3	Highly Satisfactory	5	11%	Essential

Viewer: 3D Studio Max		**Feature: Rotate**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 4	Marginal	9	17%	Essential
Subject 5	Highly Satisfactory	12	23%	Essential
Subject 6	Marginal	15	24%	Essential

QUESTION: **Ease in using the pan feature. Please rate the pan feature.**

Viewer: Cosmo		**Feature: Pan**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	6	10%	Useful
Subject 2	Highly Satisfactory	7	11%	Essential
Subject 3	Did Not Use	0	0%	N.A.

Viewer: 3D Studio Max		**Feature: Pan**		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 4	Highly Satisfactory	8	15%	Essential
Subject 5	Satisfactory	10	19%	Useful
Subject 6	Satisfactory	14	23%	Essential

QUESTION: Ease in using the tilt feature. Please rate the tilt feature.

Viewer: Cosmo		Feature: Tilt		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	4	6%	Useful
Subject 2	Satisfactory	3	5%	Useful
Subject 3	Highly Satisfactory	3	7%	Essential

QUESTION: Ease in using the go feature. Please rate the go feature.

Viewer: Cosmo		Feature: Go		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	1	2%	Useful
Subject 2	Satisfactory	2	3%	Essential
Subject 3	Highly Satisfactory	7	16%	Essential

QUESTION: Ease in using the slide feature. Please rate the slide feature.

Viewer: Cosmo		Feature: Slide		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	6	10%	Useful
Subject 2	Did Not Use	0	0%	N.A.
Subject 3	Highly Satisfactory	4	9%	Essential

QUESTION: Ease in using the undo/redo feature. Please rate the undo/redo feature.

Viewer: Cosmo		Feature: Undo/Redo		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 1	Highly Satisfactory	10	16%	Useful
Subject 2	Outstanding	4	6%	Essential
Subject 3	Highly Satisfactory	6	13%	Useful

Viewer: 3D Studio Max		Feature: Undo/Redo		
	Ease of Use	**No. Ops**	**% Ops**	**Rating**
Subject 4	Marginal	10	19%	Essential
Subject 5	Highly Satisfactory	1	2%	Essential
Subject 6	Outstanding	6	10%	Essential

QUESTION: Ease in using the remove/replace feature. Please rate the remove/replace feature.

Viewer: Cosmo		Feature: Remove/Replace		
	Ease of Use	No. Ops	% Ops	Rating
Subject 1	Highly Satisfactory	10	16%	Useful
Subject 2	Highly Satisfactory	5	8%	Essential
Subject 3	Highly Satisfactory	7	16%	Essential

Viewer: 3D Studio Max		Feature: Remove/Replace		
	Ease of Use	No. Ops	% Ops	Rating
Subject 4	Highly Satisfactory	5	9%	Essential
Subject 5	Highly Satisfactory	5	10%	Essential
Subject 6	Outstanding	2	3%	Essential

QUESTION: Ease in using the mark feature. Please rank the mark feature.

Viewer: Cosmo		Feature: Mark		
	Ease of Use	No. Ops	% Ops	Rating
Subject 1	Highly Satisfactory	8	13%	Useful
Subject 2	Highly Satisfactory	6	9%	Essential
Subject 3	Highly Satisfactory	7	16%	Essential

Viewer: 3D Studio Max		Feature: Mark		
	Ease of Use	No. Ops	% Ops	Rating
Subject 4	Highly Satisfactory	8	15%	Essential
Subject 5	Outstanding	8	15%	Essential
Subject 6	Outstanding	8	13%	Essential

QUESTION: Ease in using the information feature. Please rate the information feature.

Viewer: Cosmo		Feature: Information		
	Ease of Use	No. Ops	% Ops	Rating
Subject 1	Outstanding	3	5%	Essential
Subject 2	Highly Satisfactory	0	0%	Essential
Subject 3	Outstanding	1	2%	Essential

QUESTION: Would you have preferred a paper-based engineering drawing as opposed to a 3D graphic like the one you just manipulated in Cosmo/3D Studio Max? If so when?

There were three "no" responses, two "yes" responses, and one "depends" response to this question. There was only one maintainer who felt strongly he would prefer paper versus a fully detailed 3D model. A common comment from the maintainers was that a greater level of detail would have to be modeled for the 3D graphics to be useful. One of the maintainers said that if there was a greater level of detail and if the model provided the coordinates of the mouse pointer it would greatly reduce the time in making an assessment. Another maintainer mentioned that the system needed to somehow be integrated with an electronic version of a TO in order for it to be beneficial.

QUESTION: Could you complete the task just performed with multiple paper-based drawings or multiple pictures? If Yes, how many views would you need? Would you need views with components removed?

Five out of the six maintainers responded that they would be able to complete the task with multiple drawings. All maintainers agreed that drawings with components removed would have been necessary to adequately complete the task.

QUESTION: Would you prefer to use multiple fixed perspective paper based drawings as opposed to the 3D graphic you just used?

All six of the maintainers responded that they would prefer to use the 3D graphic model over using multiple fixed perspective paper drawings. One of the maintainers commented that it would be much easier to plot the path of the damage on the 3D model than on paper drawings. Another point was they typically have to consult multiple TOs in order to do an assessment. If a complete fully detailed 3D model was developed, the entire assessment could be accomplished more quickly using the model and viewer than the current process of consulting multiple paper TOs.

<u>QUESTION</u>: Ease in manipulation within Cosmo/3D Studio Max?

Cosmo	
	Ease of Manipulation
Subject 1	Outstanding
Subject 2	Highly Satisfactory
Subject 3	Satisfactory

3D Studio Max	
	Ease of Manipulation
Subject 4	Highly Satisfactory
Subject 5	Highly Satisfactory
Subject 6	Highly Satisfactory

<u>QUESTION</u>: Would color be helpful in the use of the 3D graphics? Why?

All six of the maintainers responded that color would be helpful in the use of 3D graphics. Three of the maintainers thought that color should be used to help identify aspects of the plane such as structure categories and dangerous areas. The structural members of the aircraft are categorized as 1-5 depending on their criticality. It was suggested that a color scheme be implemented that would allow each of the five structural categories to be easily identified in the model. For example, in the 3D model, identify all category 1 structural members using the color green and identify all of the category 2 structural members using the color blue.

Another suggestion offered by the maintainers was to use color to identify essential systems based upon the upcoming sortie type. When doing an assessment, a maintainer could tell the model that the next sortie for the aircraft is a ferry mission. Based on the sortie type, the model could dynamically adjust the colors used to identify mission essential systems for the upcoming sortie. For example, all of the essential LRUs for the ferry sortie in the radar bay would be colored in red and non-essential LRU would be colored in blue.

One of the maintainers mentioned that using color to identify electrical systems as either AC or DC would be very helpful.

QUESTION: Was the color adequate in the 3D graphics just used? Why?

All maintainer responded that the color in the 3D graphic used in the study was adequate. The colors in the model as closely as possible to resembling the actual aircraft. Two of the maintainers mentioned that it was easy on the eyes and that it made it easier to locate the damage areas. One of the maintainers commented that it was not necessary to try to match the colors in the model exactly to the aircraft because the colors are not necessarily even for the same model and block number of aircraft. The maintainer also mentioned that it would be more important to use color to identify different structural categories than to try to match the exact color of the aircraft.

QUESTION: Adequacy of color in the 3D graphics.

	Rating
Subject 1	Outstanding
Subject 2	Satisfactory
Subject 3	Outstanding
Subject 4	Satisfactory
Subject 5	Outstanding
Subject 6	Outstanding

QUESTION: Would shading be helpful in the use of 3D graphics? Why?

Four of the maintainers responded that shading would be helpful in 3D graphics. One of the maintainers that disagreed mentioned that shading would be helpful as long as shadows were not modeled. This maintainer felt that modeling shadows would cause a lot of confusion when navigating through the model. After explaining to this maintainer that, the question about shading was only intended to address shading and not shadowing, the maintainer agreed that the use of shading would be helpful. Another maintainer felt that shading is beneficial in providing visual cues to the position of the model.

The other maintainer who commented that shading would not be helpful mentioned that it hinders the assessor's ability to accurately mark the damaged areas.

QUESTION: Was the shading adequate in the 3D graphics just used? Why?

Three of the maintainers responded "yes", one "no" and one maintainer did not answer as a result of not noticing the use of shading in the 3D graphic.

QUESTION: Adequacy of shading in the 3D graphics.

The three maintainers felt the shading was an important element in making the 3D graphics more realistic.

	Rating
Subject 1	Highly Satisfactory
Subject 2	Satisfactory
Subject 3	Satisfactory
Subject 4	Satisfactory
Subject 5	Outstanding
Subject 6	Outstanding

QUESTION: Was there ever a time in the task just performed when you could not achieve a proper perspective? When specifically?

Four of the maintainers responded that they never had a problem achieving a proper perspective and two of the maintainers responded with "yes". The two maintainers that responded "yes" mentioned that with more practice, the difficulty of obtaining a proper perspective would most likely are eliminated.

QUESTON: Ease in obtaining a proper perspective.

	Rating
Subject 1	Satisfactory
Subject 2	Satisfactory
Subject 3	Satisfactory
Subject 4	Satisfactory
Subject 5	Satisfactory
Subject 6	Satisfactory

QUESTION: Could you please tell us if these requirements were met in the task just performed?

	Sub. 1	Sub. 2	Sub. 3	Sub. 4	Sub. 5	Sub. 6
Full manipulation of the 3D graphic	Y	Y	Y	Y	Y	Y
Identification of components	Y	Y	Y	Y	Y	Y
Capability to peel away layers of the 3D graphic	Y	Y	Y	Y	Y	Y
Shading used appropriately	Y	Y	Y	Y	Y	Y
Use of undo feature	Y	Y	Y	N	Y	Y
Use of multiple simultaneous views	NA	NA	NA	Y	Y	N
Use of measurement units	NA	NA	NA	Y	N	N
Use of wireframe view	NA	NA	NA	Y	Y	N
Use of orthogonal views	NA	NA	NA	Y	Y	N

QUESTON: How would you use Cosmo/3D Studio Max and the computer just used to aid in the efficiency of an assessment?

Three of the maintainers commented that by utilizing the viewer and the model, an assessment could be done more accurately and efficiently than it is currently being accomplished. However, these maintainers' comments are predicated on the fact that the level of detail of the model would have to be increased in order for the system to be used in practice. One maintainer commented that the ability to mark the damage on the model while doing an assessment would be very helpful. Once the damage has been marked on the model, it could be sent electronically to an engineer, possibly at another base, for further assessments and collaboration. Another commented that having all of the information readily available from the 3D model aided in the efficiency of an assessment, as currently the maintainer may have to consult multiple TOs to do an assessment.

The remaining maintainers felt that more detail and adequate training would be required for the model to be helpful in aiding in the efficiency of an assessment.

QUESTION: Do you have any suggestions as to the use and manipulation of 3D graphics?

All but one of the maintainers provided suggestions for this question. Some of the responses were repetitive statements of suggestions provided in previous questions. One of the

maintainers commented that the system needs to be user friendly and that the environment and conditions under which a maintainer operates needs to be taken into consideration. Another maintainer commented that the more detail the better and that links need to be provided to the textual information contained in the TOs.

Another suggestion was to provide a small image of the aircraft in the corner of the screen that tracked the user point of view in the main model. This maintainer commented that there were instances where the overall orientation was lost because the model had been zoomed in so far. The user also commented that using a large trackball, similar to ones found in arcade games, would make navigating through the model much easier.

Finally, two of the maintainers commented that the model was great and the program was off to a good start.

Preferred Viewer Features

Most of the features available to the maintainers were used. As previously stated two viewers, Cosmo and 3D Studio Max, were used in the comparative study. Although the overall ease of manipulation was rated higher for 3D Studio Max than Cosmo, a selection of one viewer over the other was not the goal of the study. To the contrary, the features contained in each viewer were the focus of concern. The viewers contained different numbers of features. The maintainers that evaluated Cosmo judged the seek, rotate, go, remove/replace, mark, and information features as being essential in the manipulation of 3D graphics. The maintainers that used 3D Studio Max stated that all the features they were presented, seek, zoom, rotate, pan, undo/redo, remove/replace and mark, were essential. When evaluating features across viewers it can be seen that the seek, rotate, remove/replace and mark features were very essential in performing the comparative study task.

Because only a subset of features in each viewer was of interest in this study, the maintainers were instructed how to use those particular features and ignore the others. For the majority of the maintainers, this was not a problem, however there were occasional uses of unapproved features. The most blatant use of restricted feature was found in Cosmo when several maintainers used the straighten feature. Although this feature was readily available, it

was not considered crucial for the manipulation of 3D graphics, thus not evaluated. However, the maintainers found the straighten feature to be extremely useful. In future studies, a wider range of features should be selected for analysis.

There were numerous suggestions for additional manipulation features that were not present in the viewers. One maintainer suggested the capability to positioning the model by entered coordinates or just the name of the damage area. Several maintainers recommended that having the ability to annotate damage on the model would be very beneficial. This statement exactly duplicated a statement made in the CTA. A depiction of the damage would only help in the assessment and repair processes.

Conclusion

The maintainers gave a favorable response to the use of a laptop computer to display 3D graphics. They suggested that they would have preferred to use a trackball or joystick rather than the external mouse used in the study. The maintainers were only given two choices of input devices, either the stick located in the center of the laptop keyboard or the external mouse. Although the graphics' realism was deemed satisfactory, there still was a call for additional detail. Within the comparative study's task, all the maintainers pointed out examples of misplaced or missing landmarks. By increasing the level of detail in the graphics, the problem with landmarks should be eliminated. When asked whether maintainers would prefer to use either the computer based 3D graphics or multiple fixed perspective paper based drawings, the majority responded that they would prefer the 3D graphics.

CONCLUSION

It has become apparent throughout the course of this study that there is a lack of research regarding the use of 3D graphics in aircraft maintenance. This work begins to address the issues involved with the potential implementation of 3D graphics within TOs. Many factors, such as graphical and 3D manipulation requirements, need to be clarified before the benefit of this technology can be fully utilized. This study has identified additional research efforts that can draw from laboratory collaboration.

Cognitive Task Analysis

The CTA served as a tool to uncover several inefficiencies that currently exist in the TO graphics and established requirements for 3D graphics. The ultimate goal of the CTA was to construct a list of requirements that candidate 3D file formats and viewers could be evaluated.

The main inefficiencies of the current TO graphics revolved around limited perspective of a graphic to describe a repair, and a lack of detail within the graphic. As described by the maintainers, the inability to change the graphic's perspective made some otherwise simple repairs very difficult. Whether it is an inside-out perspective when looking at it from outside in, or a mirror image of a wing, there are only a finite number of views that paper-based TO graphics can provide. Along with only a finite number of views, paper-based graphics are also limited by the amount of information they can contain. Another problem, which surfaced during the CTA, is the apparent lack of detail in the current TO graphics. The maintainers suggested that the level of detail in a graphic be selectable in accordance to the maintainer's background and the maintenance task being performed. For instance, an electrician and a sheet metal specialist may want to see different levels of detail when looking at an engine bay. The ability to add and remove levels of detail would be extremely beneficial. However, at any level an electronic 3D graphic should be more inapt to convey information than a traditional paper-based TO. The proposed replacement of the current graphics by 3D graphics is in an effort to correct these inefficiencies.

During the CTA, several requirements were established. These included but were not limited to the corrections of the inefficiencies mentioned above. Labeling of components,

removal of components, and having full manipulation of 3D graphics were the primary requirements gathered from the CTA. The maintainers expressed interest in having the ability to easily locate and identify components. Once having located the components, they wanted to be able to manipulate them in any manner they felt necessary in order to complete the repair. These requirements were used as selection criteria for the 3D file formats and viewers.

Technical Effort

There were three main objectives within the technical effort, 1) identification of "best value" 3D file formats by production of a file format ranking system, 2) identification of "best value" 3D viewers by production of a 3D viewer ranking system, and 3) creation of a 3D model and accompanying simulation features.

During the "best value" file format identification, the team identified and ranked industry and DoD 3D file formats. In order to rank the file formats, a set of weighted criteria were developed and used to give each of the file formats an objective numerical ranking. From ranking the file formats, it was found that VRML and SEDRIS presented the best value choices for representing 3D graphics in electronic TOs.

During the "best value" 3D viewer identifications, the team investigated several prominent 3D simulation areas: 3D modeling software, CAD packages, and virtual reality software. Similar to the file formats, a set of weighted criteria were developed and used to produce an objective ranking. From ranking the software viewers, it was found that Cosmo Player and 3D Studio Max presented the best two simulation environments for 3D viewing.

In both the production of the 3D file format ranking system and the 3D viewer ranking system, a set of objective metrics were created. These metrics and ranking systems, when applied to 3D file format and 3D viewer products, can objectively determine the best products for the aircraft maintenance task. Although the "best of the best" have been determined at this point in time, the 3D graphics market is a market in constant flux, rendering the best products obsolete in a matter of months. These ranking systems can help determine the best products in new markets and are intended for reuse in the future.

Finally, in support of the comparative study, a 3D model of an F-15 aircraft with a detailed model of bay 3R was built. This model was used in conjunction with the two best file formats and 3D viewers to create two models. These models included the F-15 aircraft model as well as the implementation of several core features which had been established as requirements from the CTA: namely, the abilities to remove and replace components, fully manipulate the 3D graphics, and to label components.

Comparative Study

The comparative study was conducted to determine the extent to which 3D graphics would be useful and potentially benefit ABDR maintenance. Because of time and funding constants, both of these questions were only addressed though a questionnaire rather than a performance study. All but one of the six maintainers that participated in the study stated in the questionnaire that 3D graphics and viewers were easy to use. The majority of the maintainers responded that they never experienced a problem achieving a proper perspective of the 3D graphics. Three maintainers commented that with an increased level of detail in the graphics they could conduct assessments more accurately and efficient than what is currently being accomplished.

The comparative study also substantiated the 3D graphic requirements established in the CTA along with gathering additional requirements. These additional requirements were prompted by the illustration of the 3D model used in the comparative study task. Once the maintainers could associate the functionality of an actual 3D model with a maintenance task, they provided comments that are much more detailed.

The comparative task analysis, technical effort and the comparative study all combined to establish some basic requirements for 3D graphics within maintenance. However, these alone did not spell out the work yet to be done before this technology can be operational. There are numerous areas of further research.

Areas for Further Study

A list of 3D graphical requirements formed from the CTA was presented to the maintainers who participated in the comparative study. When asked if the 3D graphic and viewer

combination used in the comparative task met these requirements, an overwhelming "yes" prevailed. This implies that the use of 3D graphics has already displayed the capability of meeting the maintainer's current requirements. However, there were several suggestions that would increase the likelihood of acceptance. Additional user friendliness of the 3D viewer's GUI, an increased level of situation awareness of their repair locations within the aircraft, and additional graphical detail were mentioned as essential improvements.

A fundamental issue of concern is the level of graphical detail – and therefore realism - required. Two contributing (and unfortunately, opposing) factors play a large part: frame rate and model complexity. Frame rate is ultimately determined by the amount of model complexity; simple models present high frame rates due to the small amount of computations required to render. Complex models create more work, and allow the computer to update the screen less often. Both high frame rates and complex models add to realism, indicating the need to research the balance between frame rate vs. graphical detail.

Throughout the course of the study, several questions arose concerning the viability and efficiency of electronic TOs when compared to the current paper-based TOs, even more specifically the use of 3D graphics within electronic TOs compared to the current method of performing maintenance. Although there is a trend to modernize current practices in the Air Force the impact of such modernization is not always fully evaluated prior to application. Questions like these need to be evaluated and tested thoroughly to fully understand and steer technology to the best possible solution for all involved.

The comparative study resolved quite a few practical concerns regarding the conditions in which maintainers perform repairs. The optimal hardware configuration (e.g., input device) needs to be investigated. Environmental conditions must also be considered for the usability of electronic TOs to be fully determined. The maintainers that participated in the study conveyed that they often work in chemical gear to perform repairs. Issues such as clothing and the environment conditions need to be evaluated.

Several media have been studied for use in displaying electronic TOs to the maintainers. This study used a laptop computer to display and manipulate 3D graphics. Another common approach is the use of wearable computing systems with Head-Mounted Displays (HMD) to

display TOs. There are many application questions to be answered for both of these media in relation to 3D graphics. A study to evaluate these issues would guide development.

The creation of the F-15 model in the investigation revealed the need to create or find suitable 3D models. Although the model can be created from scratch, time and effort could be saved from finding (and converting) existing models from other simulation systems. To use such a model there appear a subset of problems which must be overcome to use the data, namely:

1) Is the data in a usable file format or can it be converted into a usable file format? Although aircraft can be designed digitally, they may have been designed in a proprietary system – meaning legal considerations will have to be taken into account. Additionally, the model may have been designed in a system which uses its own way of storing data – and its own file format, meaning file format conversions will have to be taken into account.

2) Is the data too complex to use? The amount of data presented in the file format may well be far more than can be currently handled by the systems needed. If so, the process of distillation from the original set of data to the needed set of data will need to be investigated.

Throughout the study several maintainers stated repetitively that the utilizing 3D graphics would benefit maintenance training. These suggestions were given a lot of consideration especially since a few of the maintainers participating in the study were ABDR instructors. Although it may have been the consensus of the group that 3D graphics could quicken the pace of training in a more efficient manner, the substantiation of this hypothesis was never the focus the study. A much more detailed project would need to be designed that specifically addresses this question.

Along those same lines, the maintainers were asked whether they thought 3D graphics would aid in ABDR assessments, after they completed the comparative study task. Again, although the majority of the maintainers felt that 3D graphics would make the assessment process more efficient, this was never tested. A follow-on study that could compare the current

method of performing assessments with a new method that utilized 3D graphics could address this question.

Although these research opportunities only represent a subset of the potential issues involved with implementing 3D graphics in aircraft maintenance they provide a base from which to start. With any implementation of new technology, there are many challenges.

It became very evident through this research effort sponsored by AFRL/HESR that the graphics prevalent with in the current paper based TOs are routinely inadequate and sometimes even misleading. The team feels that this effort provided for a great first step in helping identify some of the problems and issues with the current graphics as well as investigating a new alternative, 3D graphics. With the continual advances in computer hardware and software arena, along with continuing innovated research efforts spearheaded by AFRL, the reality of providing fully manipulatable 3D graphics for use in electronic TOs is attainable now.

Glossary

BACKFACING: Method of reducing polygons drawn by the simulation by calculating the normal to the polygon's surface.

BROWSER: Software package that can display Hypertext Markup Language (HTML) pages.

DATA VISUALIZATION: The ability to display a set of data in a graphical form.

DESIGN PROTOTYPING SOFTWARE: Software, usually related to CAD packages, which allows objects such as vehicles or aircraft to be designed in a simulated environment. Objects are usually designed with real-world purposes in mind.

DIGITAL PICTURE: A set of data that represents a 2D image.

FRAME RATE: Measurement of how often the simulated environment's screen is updated per second.

MODELING SOFTWARE: Software package which allows objects to be designed in a simulated environment. Objects are usually designed to be used in other simulated environments.

MOVEMENT PARADIGM: A method for movement though a simulated environment that mimics real life movement, such as walking, flying, driving, etc.

PLUG-IN: A software package that works in conjunction with a browser. The plug-in adds some functionality to the browser which the browser did not originally have. In most cases in this investigation, the plug-in added the ability to view a 3D simulated environment.

POLYGONS: Flat planes created by interconnecting vertices.

ROTATION: The ability to rotate an object or eyepoint in a simulated environment.

STAND-ALONE: A software package which performs a task with no additional plug-ins needed for support.

3D FILE FORMAT: A protocol for a set of data which represents a 3D object.

3D FILE FORMAT CONVERTER: Software that can import a 3D file format, understand its contents, and export those contents as another 3D file format.

3D VIEWER: Software that allows the data contained in a 3D file format to be presented onscreen in a 3D simulated environment.

TIMESENSOR: An object in a VRML 2.0 simulated environment. TimeSensors have multiple functionality; the function used in this investigation was to display animation frames at particular intervals.

TOUCHSENSOR: An object in a VRML 2.0 simulated environment, used to determine mouse click input from the user.

TRANSLATION: The ability to move an object or eyepoint in a simulated environment from one position to another.

VERTICES: Three dimensional (x,y,z) points in a 3D simulated environment.

VIRTUAL REALITY SOFTWARE: Software package that displays a 3D simulated environment.

WIREFRAME: A method of displaying simulated environments in which all objects in the simulation appear to be a collection of lines with no surfaces.

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Appendix A
Background Information Questionnaire

Subject Number:________
Scenario Type: ABDR

Aircraft Maintainer Information Questionnaire

Name: ____________________________________

Date: ____________________________________

Title/Rank: ________________________________

AFSC: ____________________________________

Organizational Affiliation: __________________

AF Base: __________________________________

Office Phone: ______________________________

Type of Aircraft Maintained	Approximate Months/Years	AF Base	Specialization	Experience

Subject Number:________
Scenario Type: ABDR

Aircraft Maintainer Information Questionnaire

Name: ______________________________

Date: ______________________________

Title/Rank: ______________________________

AFSC: ______________________________

Organizational Affiliation: ______________________________

AF Base: ______________________________

Office Phone: ______________________________

Type of Aircraft Maintained	Approximate Months/Years	AF Base	ABDR Assessor Qualified	ABDR Specific Qualified

Appendix B

Maintenance Task Scenarios

Routine

FOREIGN OBJECT DAMAGE (FOD):

"You were working in the cockpit and you dropped a screw, please walk us through your process of finding it."

BRAKE CHANGE:

"Could you please walk us through a routine brake change?"

INSPECTIONS BY FEEL:

"Has there ever been a time you performed an inspection or repair in which you had to rely solely on feel because there was no visual accessibility? What modifications did you have to make to your inspection and repair processes to compensate for your inability to view the problem area?"

PERSPECTIVE PROBLEM:

"Have you ever encountered a problem with the perspective view of a T.O. graphic (figure)? If so, can you recall a particular example of when a graphic's perspective complicated your repair?"

ABDR

CREW CHIEF:

"Could you please walk us through your inspection process for an airplane returning from battle? Are there requirements that must be performed strictly by feel because there is no visual accessibility? If so, could you please describe them?"

ELECTRICIAN:

"You run across a broken or damaged wire bundle, please walk us through your process of identifying what needs to be repaired. Such as- identifying where the wires travel throughout the aircraft, identifying the bulk heads they connect to, and locating their termination points."

SHEET METAL:

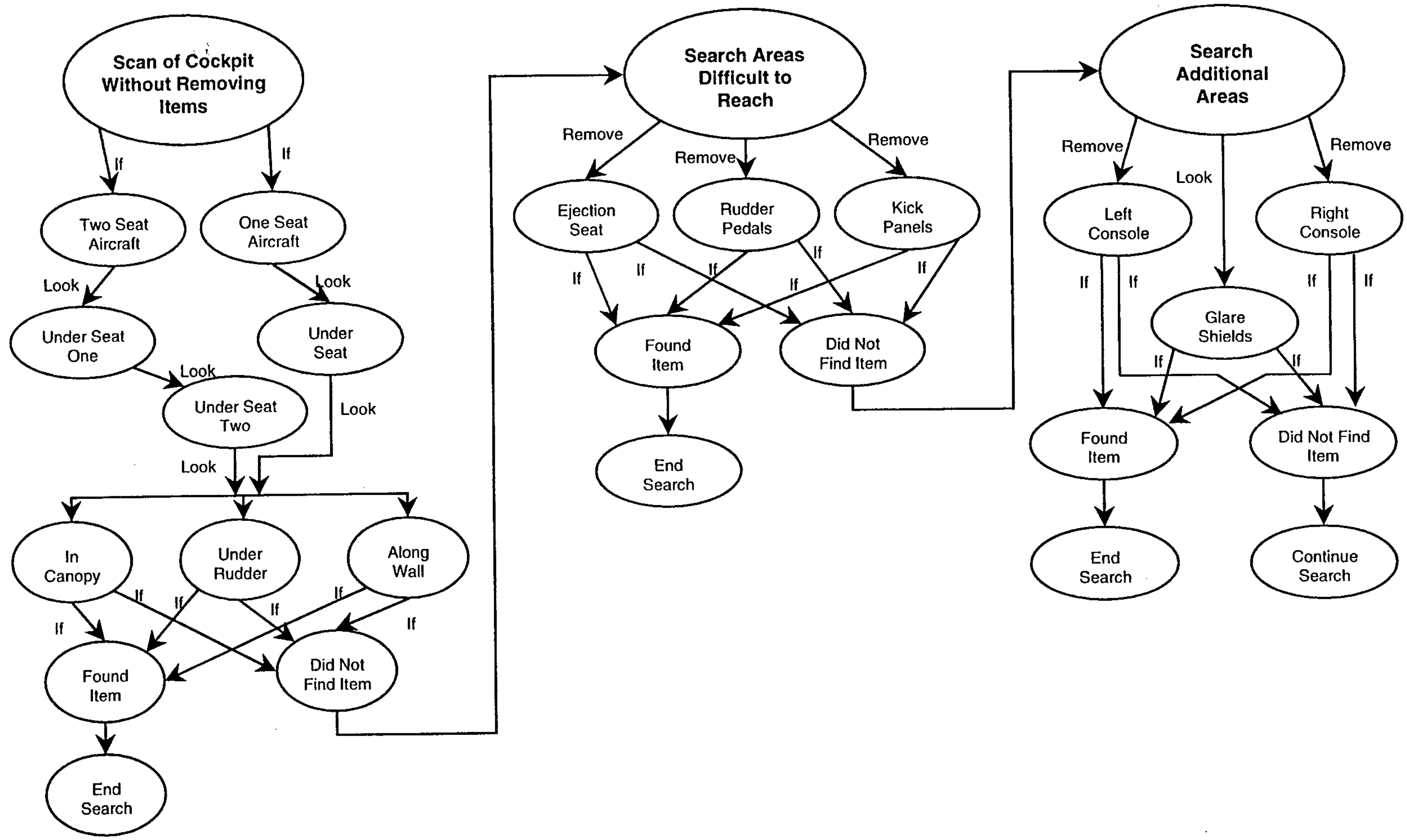
"When you assess and repair a damaged aircraft what techniques do you use to keep from causing more damage?"

Appendix C

CTA Concept Maps

Scenario: Foreign Object Damage (FOD)

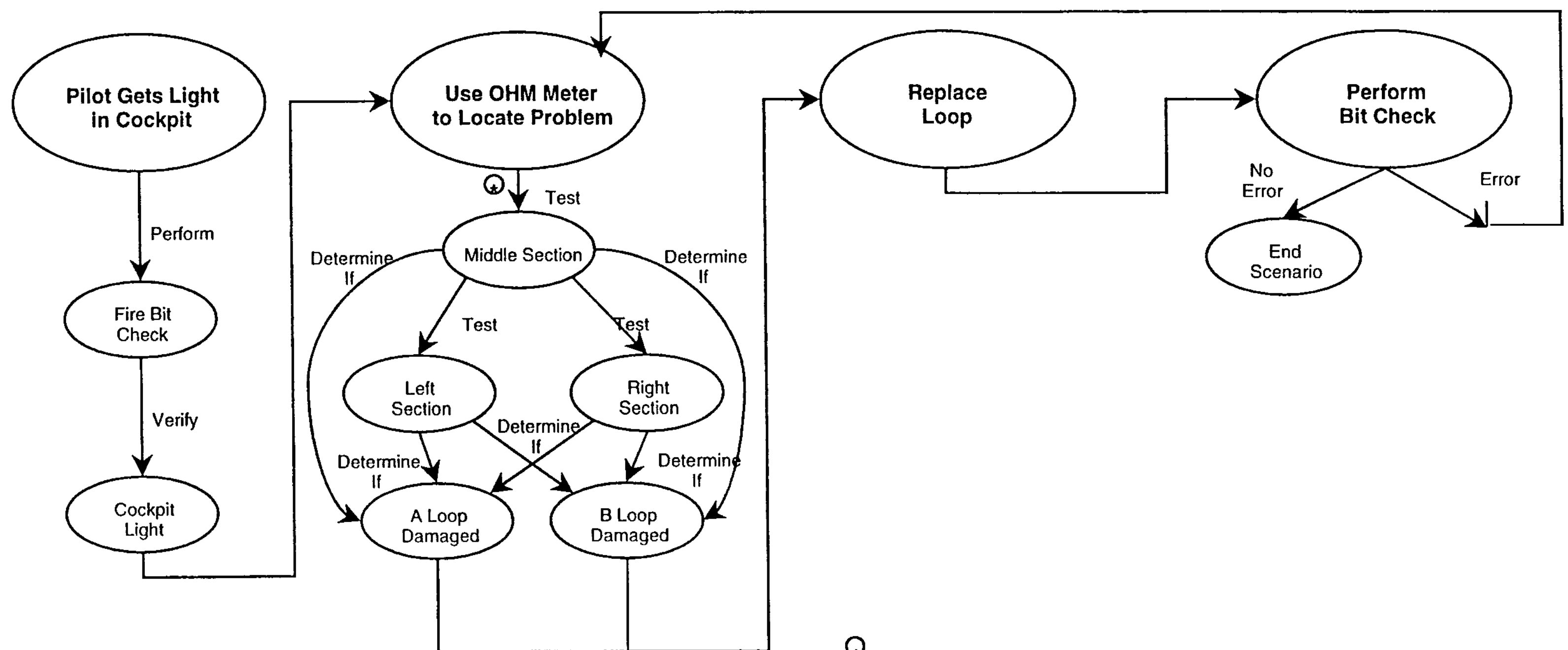
ROUTINE MAINTENANCE SCENARIO
SUBJECT 1
2/12/98



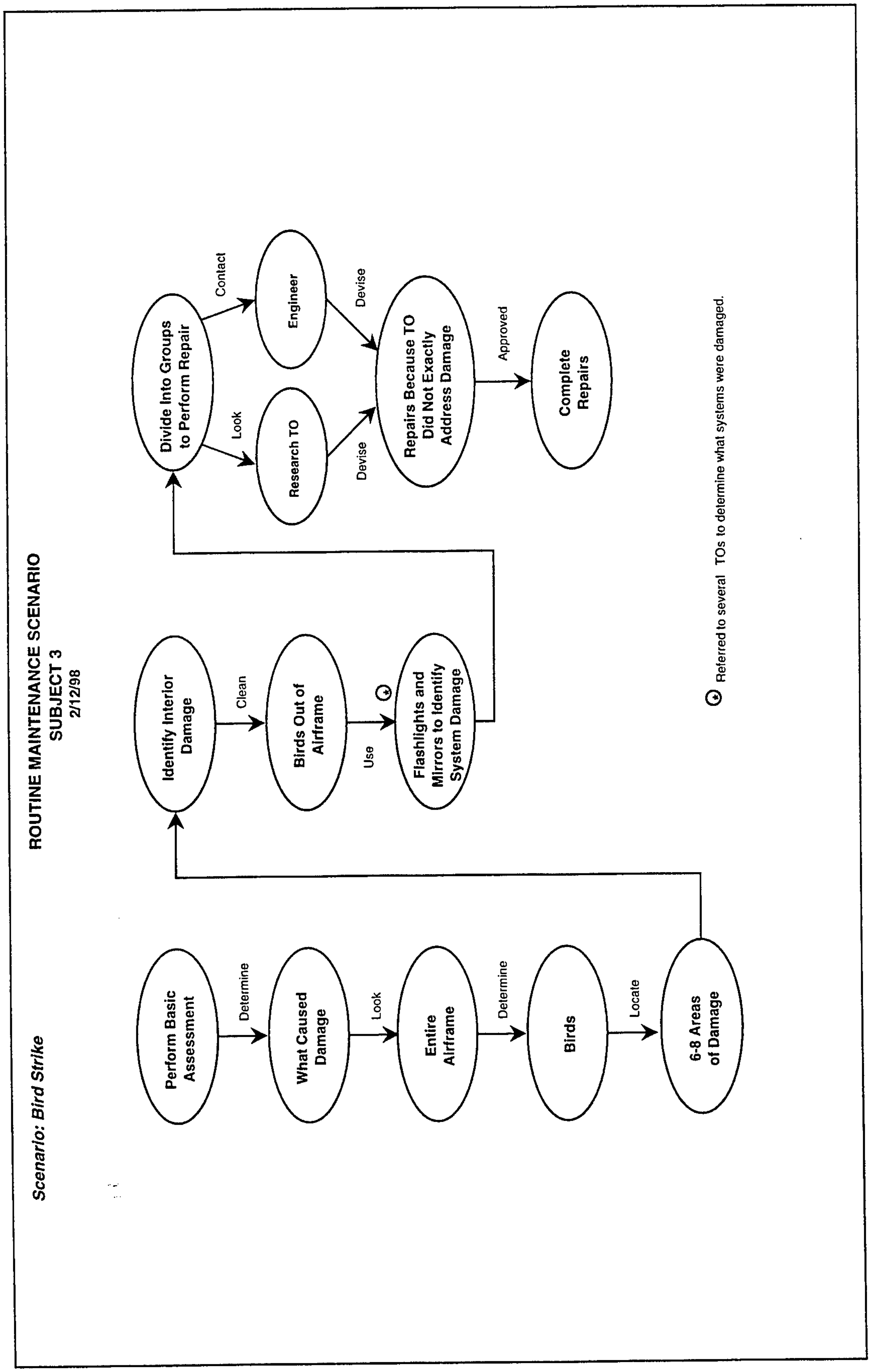
Notes:
- Only a novice unfamiliar with the aircraft would reference TO graphics.
- Graphics are typically not required because if a difficult removal is required, a specialist will be called.

Scenario: Fire Loop (Electrical Component)

ROUTINE MAINTENANCE SCENARIO
SUBJECT 2
2/12/98



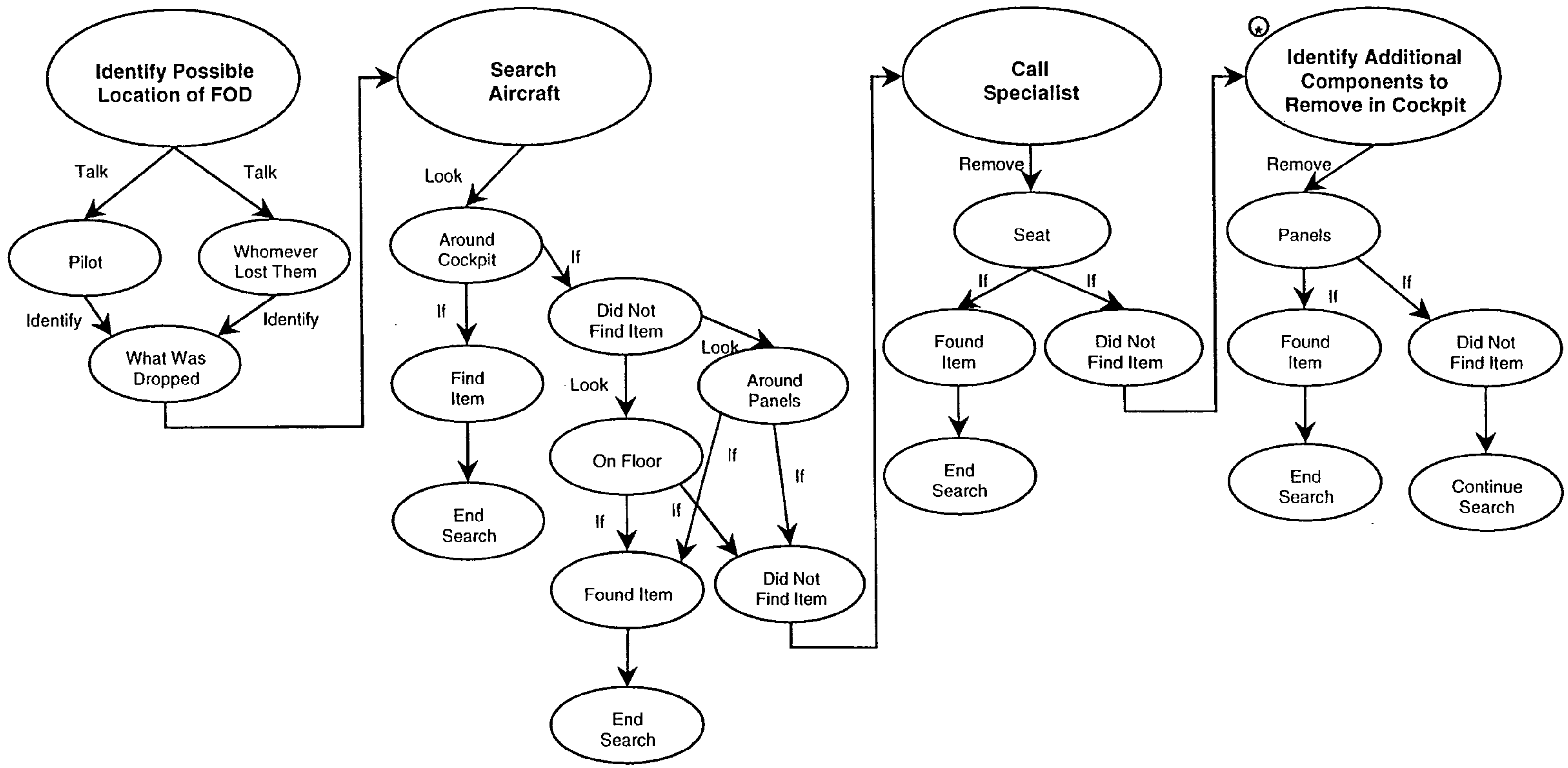
Novice would need to reference TO graphic in order to locate the fire loops.



ROUTINE MAINTENANCE SCENARIO
SUBJECT 3
2/12/98
Scenario: Bird Strike
Perform Basic Assessment
Determine
What Caused Damage
Look
Entire Airframe
Determine
Birds
Locate
6-8 Areas of Damage
Identify Interior Damage
Clean
Birds Out of Airframe
Use
Flashlights and Mirrors to Identify System Damage
Divide Into Groups to Perform Repair
Look
Research TO
Contact
Engineer
Devise
Devise
Repairs Because TO Did Not Exactly Address Damage
Approved
Complete Repairs
Referred to several TOs to determine what systems were damaged.

Scenario: Foreign Object Damage (FOD)

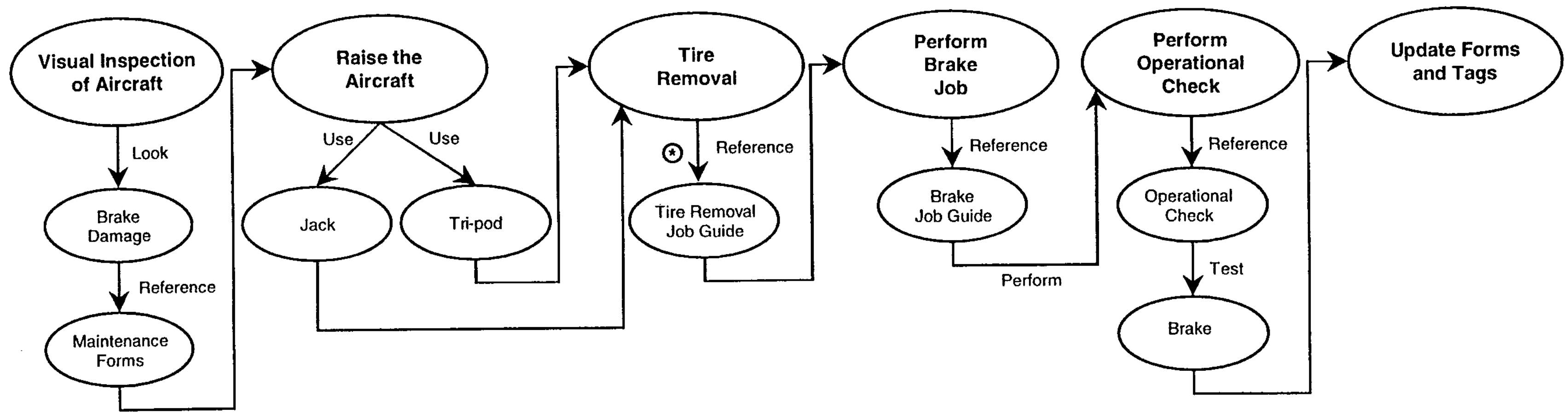
ROUTINE MAINTENANCE SCENARIO
SUBJECT 4
2/12/98



TO Graphics would be referenced to identify all removable items in the cockpit.

Scenario: Brake Change

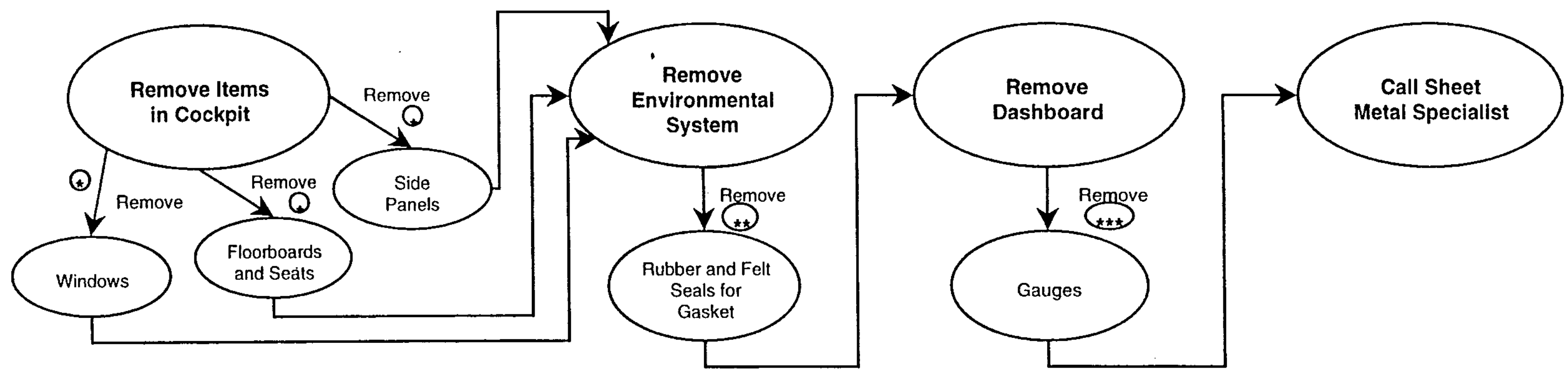
ROUTINE MAINTENANCE SCENARIO
SUBJECT 5
2/13/98



(*) Not all of the related information regarding brake change is found in Job Guide.
Need several TOs and Job Guides to complete tire change.

Scenario: C-141 Window Post Repair

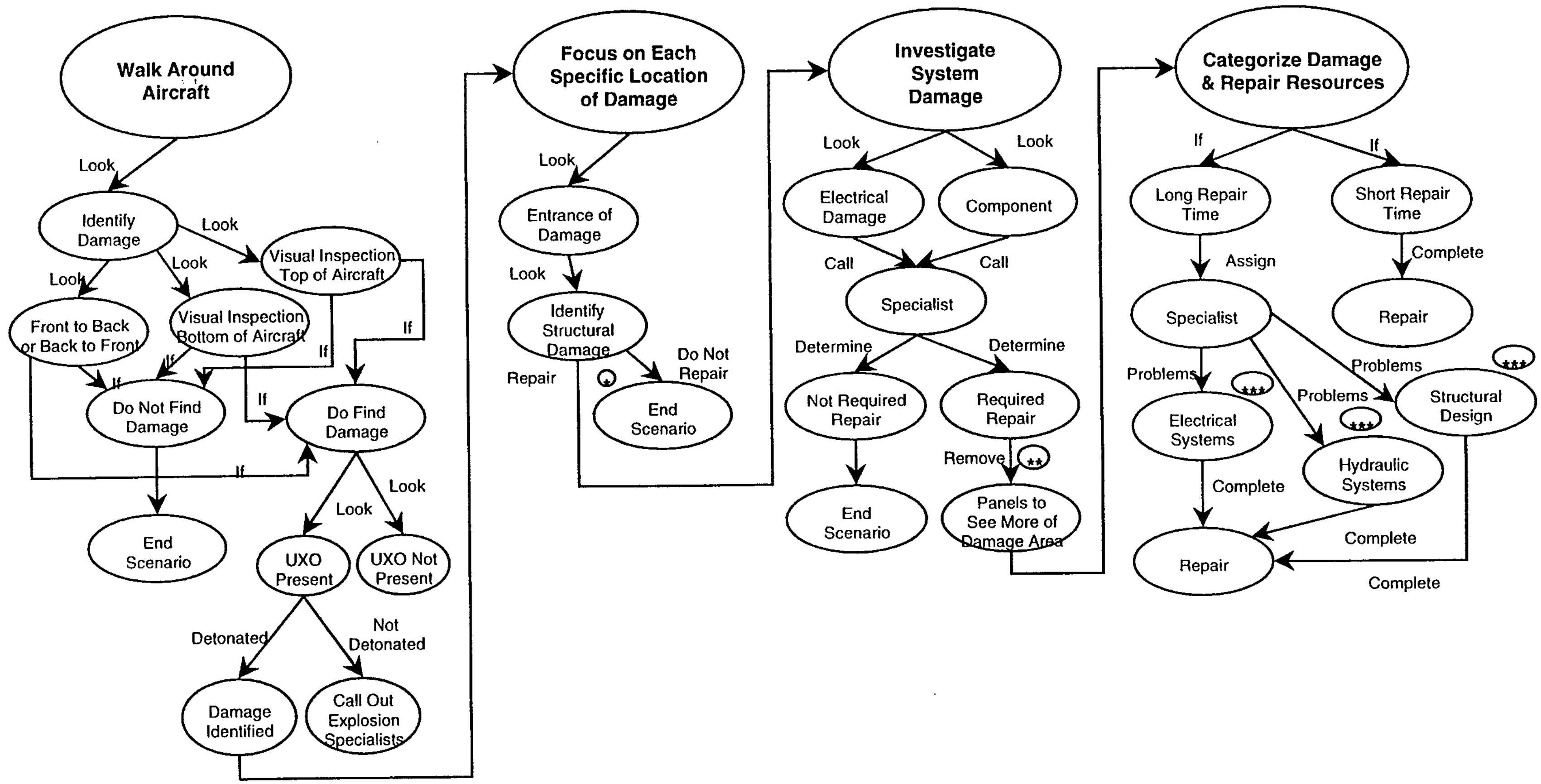
ROUTINE MAINTENANCE SCENARIO
SUBJECT 6
2/13/98



Referred to TO and Job Guides. Graphics do not clearly show location of parts.
** TOs did not show which side of seal faced outside.
*** Bolt locations are not shown inTOs.

Scenario: Crew Chief

ABDR MAINTENANCE SCENARIO
SUBJECT 1
2/12/98



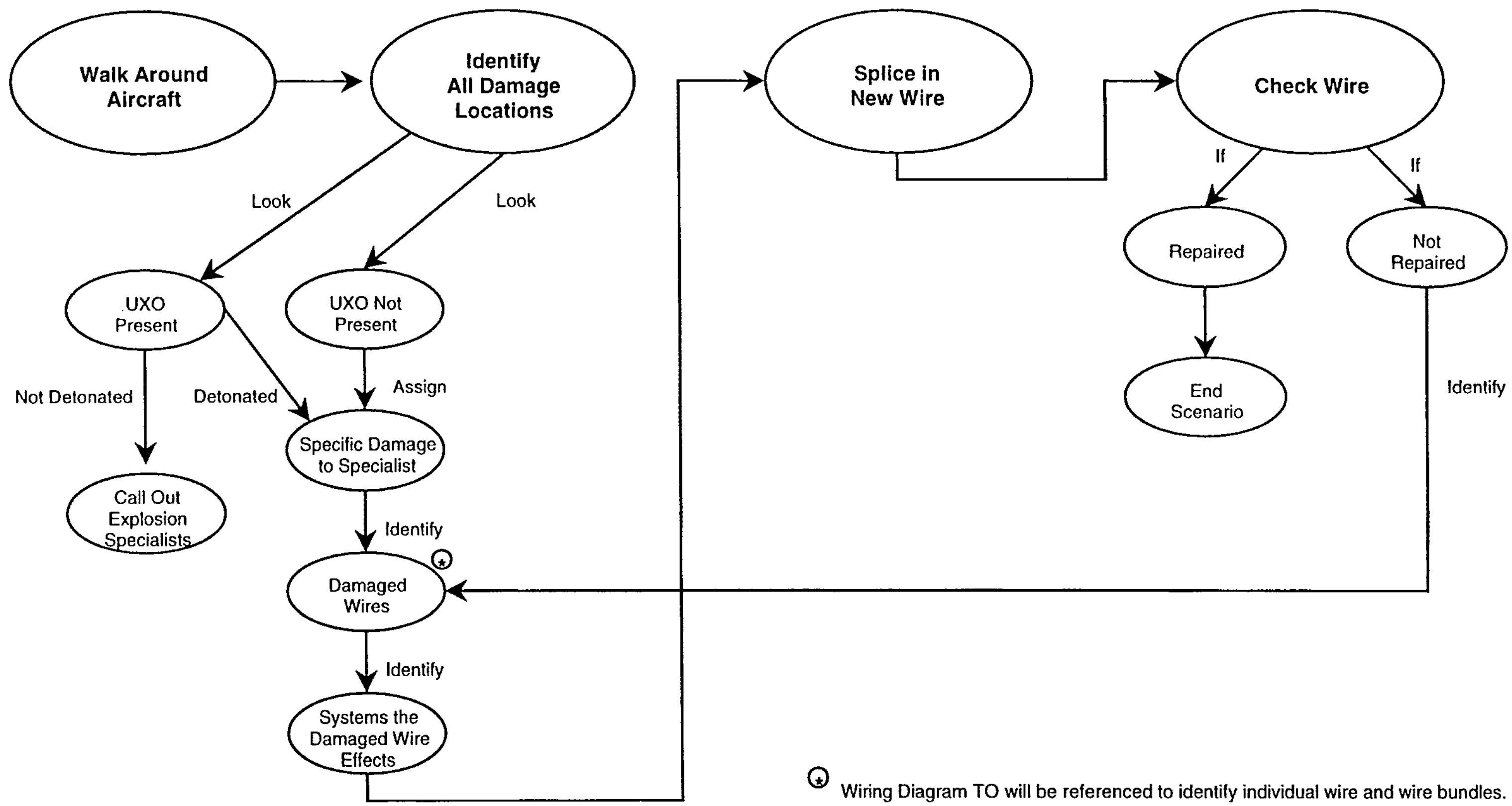
Novice would need to reference a TO to determine if an aircraft is repairable.

** 3-D Graphics would aid in allowing the maintainer to see what components lie behind a damaged panel before the panel is removed.

*** 3-D Graphics would aid maintainers by allowing the entire plane to be viewed at one time.

Scenario: Electrical

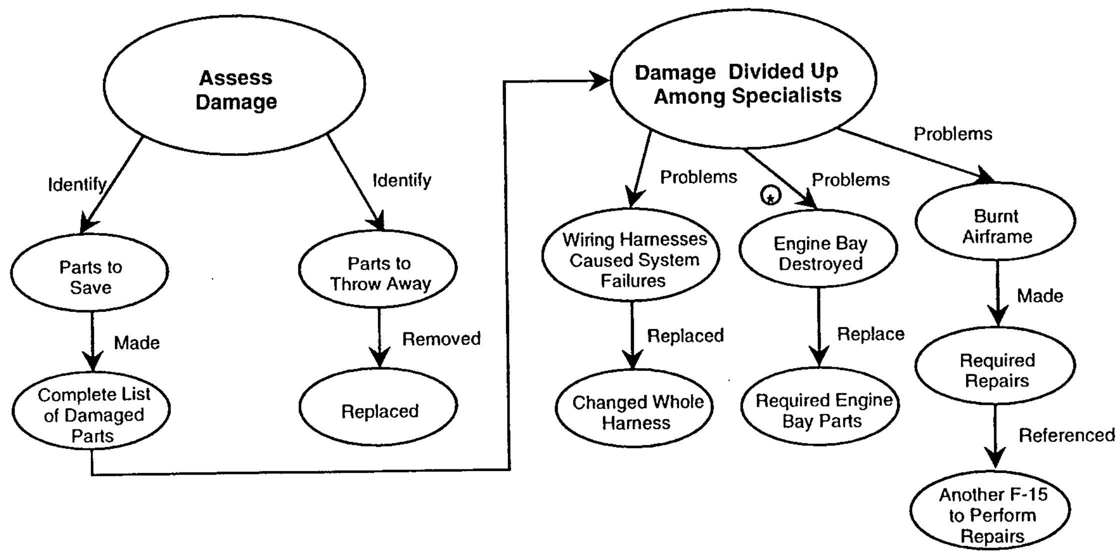
ABDR MAINTENANCE SCENARIO
SUBJECT 2
2/12/98



* Wiring Diagram TO will be referenced to identify individual wire and wire bundles.

Scenario: Sheet Metal (Burn Damage)

ABDR MAINTENANCE SCENARIO
SUBJECT 3
2/12/98

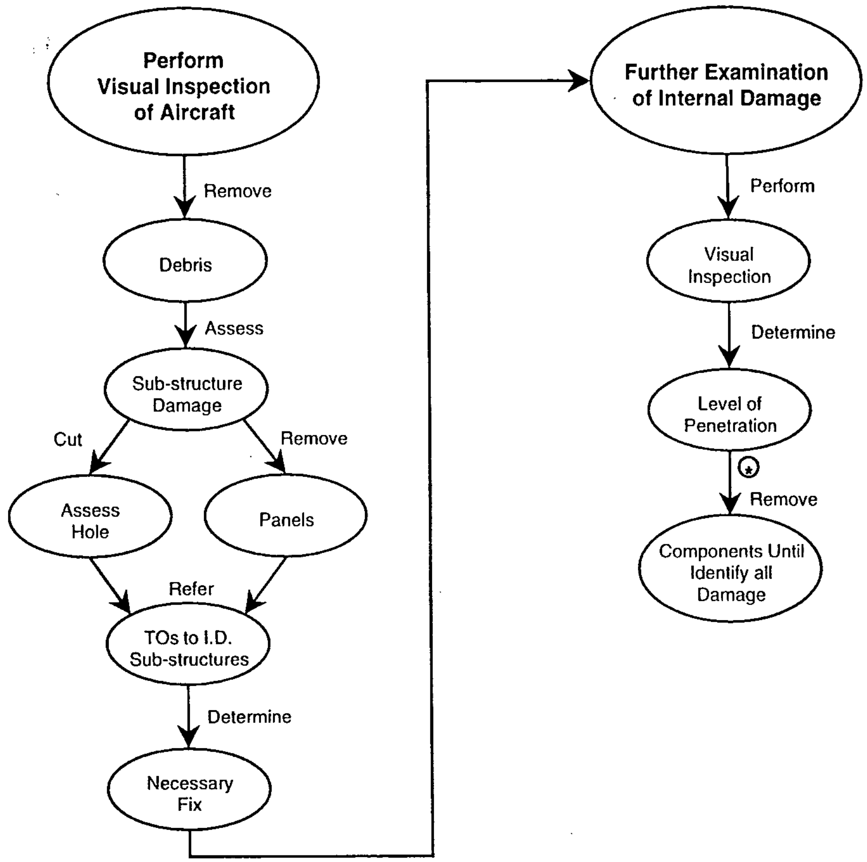


3-D Graphics would aid in repair of the engine bay.

Note: Only TOs referenced were by crew chiefs and electricians for routing purposes. Majority of work was based on engineering drawings.

Scenario: Sheet Metal

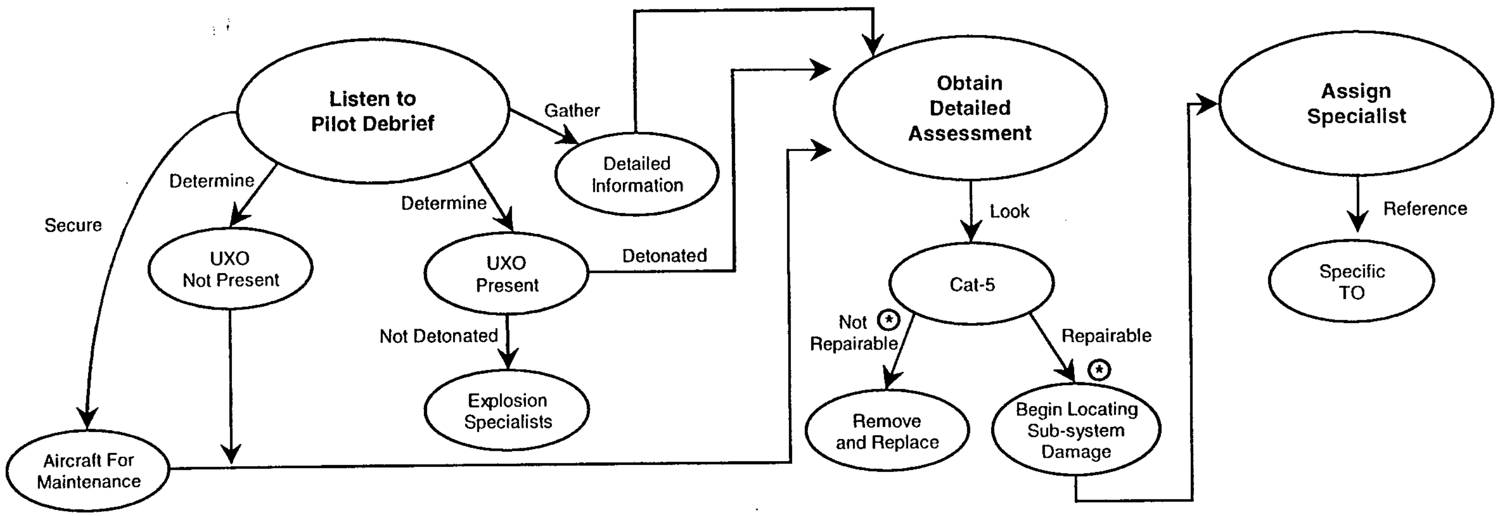
ABDR MAINTENANCE SCENARIO
SUBJECT 4
2/12/98



(*) Reference TO to identify layers of components that may be damaged.

Scenario: Crew Chief

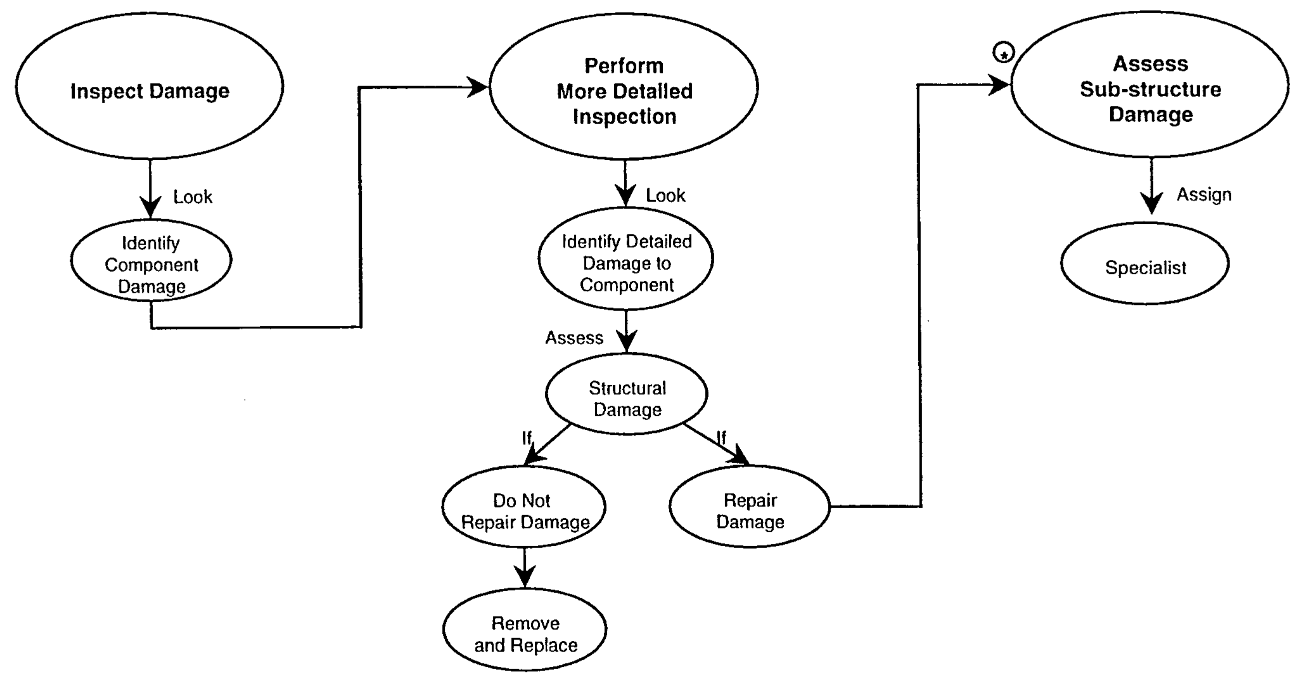
ABDR MAINTENANCE SCENARIO
SUBJECT 5
2/13/98



(*) 3-D Graphics would be beneficial in assessing damage multiple layers of the aircraft could be viewed.

Scenario: Crew Chief

ABDR MAINTENANCE SCENARIO
SUBJECT 6
2/13/98



Reference TO to identify sub-system damage

Appendix D

Comparative Study Background Information Questionnaire

CSubject Number: ____________________

Viewer: Cosmo World - 3D Studio Max

Input device: Stick Mouse

Aircraft Maintainer Information Questionnaire

Name: ____________________________________

Date: ____________________________________

Title/Rank: ________________________________

AFSC: ____________________________________

Organizational Affiliation: ______________________

AF Base: __________________________________

Office Phone: _______________________________

Do you have a home computer? Yes _____ No______

Computer Experience: ______ months / years

____

____

____

Do you have experience with 3D graphics? Yes______ No______

If yes, how many years? ________

Do you have experience with 3D graphic viewers (application which allows you to view and manipulate 3D graphics? Yes______ No______

If yes, which ones?____

Appendix E

Cosmo and 3D Studio Questionnaires

Name:____________________ **Date:**____________________

Subject:____________________ **No.Viewer: Cosmo 2.1**

Comparative Study Questionnaire

1. Were the 3D graphics easy to use? Yes No

   Why? ____

2. Did the laptop computer hinder your ability to use the 3D graphics? Yes No

   Why? ____

3. Adequacy of the screen size for displaying the 3D graphics.

   Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

4. Adequacy of the input device for manipulating the 3D graphics.

   Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

5. Use of the laptop computer as a tool to manipulate the 3D graphics.

   Outstanding | Highly. Satisfactory | Satisfactory | Marginal | Unsatisfactory

6. Were the 3D graphics displayed in this task realistic and reliable? Yes No

   Why? ____

7. Realism of the 3D graphics.

   Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

8. Were there any misplaced or missing landmarks in the 3D graphics? Yes No
If there were, did they cause problems in the scenario? Yes No

Why? ____

____

9. Could you please provide examples of additional manipulation features that would be helpful?

____

____

____

10. Please mark the features you used in the task just performed:

Seek
Zoom
Rotate
Pan
Tilt
Go
Slide
Undo/Redo
Remove/Replace
Mark
Information

11. Ease in using the seek feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

12. Please rate the seek feature.

Essential | Useful | Useless

13. Ease in using the zoom feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

14. Please rate the zoom feature.

Essential | Useful | Useless

15. Ease in using the rotate feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

16. Please rate the rotate feature.

Essential | Useful | Useless

17. Ease in using the pan feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

18. Please rate the pan feature.

Essential | Useful | Useless

19. Ease in using the tilt feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

20. Please rate the tilt feature.

Essential | Useful | Useless

21. Ease in using the go feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

22. Please rate the go feature.

Essential | Useful | Useless

23. Ease in using the slide feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

24. Please rate the slide feature.

Essential | Useful | Useless

25. Ease in using the undo/redo feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

26. Please rate the undo/redo feature.

Essential | Useful | Useless

27. Ease in using the remove/replace feature

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

28. Please rate the remove/replace feature.

Essential | Useful | Useless

29. Ease in using the mark feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

30. Please rate the mark feature.

Essential — Useful — Useless

31. Ease in using the information feature.

Outstanding — Highly Satisfactory — Satisfactory — Marginal — Unsatisfactory

32. Please rate the information feature.

Essential — Useful — Useless

33. Would you have preferred a *paper engineering drawing* as opposed to a 3D graphic like the one you just manipulated in Cosmo? Yes No

If so when? ____________________

____

34. Could you complete the task just performed with multiple *paper based drawings* or multiple pictures? Yes No

If Yes, how many views would you need? ___

Would you need views with components removed? Yes No

35. Would you prefer to use multiple fixed *perspective paper based drawings* as opposed to the 3D graphic you just used? Yes No

Why? ____________________

____

36. Ease in manipulation within Cosmo.

Outstanding — Highly Satisfactory — Satisfactory — Marginal — Unsatisfactory

37. Would color be helpful in the use of the 3D graphics? Yes No

Why? ____________________

____

38. Was the color adequate in the 3D graphics just used? Yes No

Why? ____

____

39. Adequacy of color in the 3D graphics.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

40. Would shading be helpful in the use of 3D graphics? Yes No

Why? ____

____

41. Was the shading adequate in the 3D graphics just used? Yes No

Why? ____

____

42. Adequacy of shading in the 3D graphics.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

43. Was there ever a time in the task just performed when you could not achieve a proper perspective? Yes No

When specifically? ____

____

44. Ease in obtaining a proper perspective.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

45. Could you please tell us if these requirements were met in the task just performed?

Full manipulation of the 3D graphic-	Yes	No
Identification of components (text)-	Yes	No
Capability to peel away layers of the 3D graphic-	Yes	No
Color used appropriately-	Yes	No

Shading used appropriately-	Yes	No
Use of undo feature-	Yes	No
Use of multiple simultaneous views-	Yes	No
Use of measurement units-	Yes	No
Use of wireframe view-	Yes	No
Use of orthogonal views-	Yes	No

46. How would the use Cosmo, 3D graphics, and the computer just used aid in the efficiency of an assessment?

____

____

____

47. Do you have any suggestions as to the use and manipulation of 3D graphics?

____

____

____

Name: ____________________ Date: __________

Subject No.___ Viewer: 3D Studio

Comparative Study Questionnaire

48. Were the 3D graphics easy to use? Yes No

Why? ____

____

49. Did the laptop computer hinder your ability to use the 3D graphics? Yes No

Why? ____

____

50. Adequacy of the screen size for displaying the 3D graphics.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

51. Adequacy of the input device for manipulating the 3D graphics.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

52. Use of the laptop computer as a tool to manipulate the 3D graphics.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

53. Were the 3D graphics displayed in this task realistic and reliable? Yes No

Why? ____

____

54. Realism of the 3D graphics.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

55. Were there any misplaced or missing landmarks in the 3D graphics? Yes No
If there were, did they cause problems in the scenario? Yes No

Why? ____

____

56. Could you please provide examples of additional manipulation features that would be helpful?

____

____

____

57. Please mark the features you used in the task just performed:

Seek
Zoom
Zoom Extents
Rotate
Pan
Undo/Redo
Remove/Replace
Mark
Information

58. Ease in using the seek feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

59. Please rate the seek feature.

Essential | Useful | Useless

60. Ease in using the zoom feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

61. Please rate the zoom feature.

Essential | Useful | Useless

62. Ease in using the zoom extents feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

63. Please rate the zoom extents feature.

Essential | Useful | Useless

64. Ease in using the rotate feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

65. Please rate the rotate feature.

Essential | Useful | Useless

66. Ease in using the pan feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

67. Please rate the pan feature.

Essential | Useful | Useless

68. Ease in using the undo/redo feature.

Outstanding | Highly Satisfactory | Satisfactory | Marginal | Unsatisfactory

69. Please rate the undo/redo feature.

Essential | Useful | Useless

70. Ease in using the remove/replace feature.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

71. Please rate the remove/replace feature.

Essential	Useful	Useless

72. Ease in using the mark feature.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

73. Please rate the mark feature.

Essential	Useful	Useless

74. Ease in using the information feature

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

75. Please rate the information feature.

Essential	Useful	Useless

76. Would you have preferred a *paper engineering drawing* as opposed to a 3D graphic like the one you just manipulated in Cosmo? Yes No

If so when?____

____

77. Could you complete the task just performed with multiple *paper based drawings* or multiple pictures? Yes No

If Yes, how many views would you need? ___

Would you need views with components removed? Yes No

78. Would you prefer to use multiple fixed *perspective paper based drawings* as opposed to the 3D graphic you just used? Yes No

Why? ____

____

79. Ease in manipulation within 3D Studio Max.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

80. Would color be helpful in the use of the 3D graphics? Yes No

Why? ____

____

81. Was the color adequate in the 3D graphics just used? Yes No

Why? ____

____

82. Adequacy of color in the 3D graphics.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

83. Would shading be helpful in the use of 3D graphics? Yes No

Why? ____

____

84. Was the shading adequate in the 3D graphics just used? Yes No

Why? ____

____

85. Adequacy of shading in the 3D graphics.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

86. Was there ever a time in the task just performed when you could not achieve a proper perspective? Yes No

When specifically? ______________________________

____

87. Ease in obtaining a proper perspective.

Outstanding	Highly Satisfactory	Satisfactory	Marginal	Unsatisfactory

88. Could you please tell us if these requirements were met in the task just performed?

Full manipulation of the 3D graphic-	Yes	No
Identification of components (text)-	Yes	No
Capability to peel away layers of the 3D graphic-	Yes	No
Color used appropriately-	Yes	No
Shading used appropriately-	Yes	No
Use of undo feature-	Yes	No
Use of multiple simultaneous views-	Yes	No
Use of measurement units-	Yes	No
Use of wireframe view-	Yes	No
Use of orthogonal views-	Yes	No

89. How would the use 3D Studio Max, 3D graphics, and the computer just used aid in the efficiency of an assessment?

____

____

____

90. Do you have any suggestions as to the use and manipulation of 3D graphics?

____

____

____

Appendix F

Comparative Study Protocol

Comparative Study Protocol
Robins Air Force Base
18-21 May

The Comparative Study consisted of the following five sections, which are explained below:

1. Training
2. Scenario Description
3. Task
4. Data Collection
5. Questionnaire

No fewer than six maintainers participated in the Comparative Study. Each maintainer received only one 3D viewer to evaluate. The Comparative Study lasted two hours per maintainer.

1. Training (30 minutes)

Computer
- The maintainers were given time to become familiar with the laptop computer.

Input Device
- The maintainers were asked to select one of the following input devices:
    a. External mouse
    b. Stick located in middle of laptop keyboard
- If necessary, the maintainers were given time to become familiar with using a mouse by playing a game of Solitaire.

Viewers
- The maintainers were instructed how to use all the features required to complete the task (i.e., zoom, pan, rotate, remove, replace, mark, and walk) for their particular viewer.
- The maintainers were asked to perform the following simple tasks to test their ability to use the required features.
    a. Box sitting on something (start with a far away view and have them *zoom* and *pan*)
    b. Box with something written on each side (allows them to *rotate* and *walk* the box to read each of the sides)
    c. Box with a circle inside (allows them to click on the box and then have it disappear and the circle inside appear, *remove* and *replace*)
    d. Box with a bulls-eye on two sides (allows them to place a *mark* (cursor) inside the bulls-eye)
- Training was completed when the maintainers could perform all the above actions without assistance.

2. Scenario Description (include time for training)

- The maintainers were given the following scenario:

  "During a pilot de-brief the pilot explains that shortly after sustaining a hit the radar became locked. You are instructed to identify and repair the problem."

3. Task (30 minutes)

The maintainers proceeded to the plane with the laptop after the scenario had been explained. Once at the plane, they were told to experiment with the view and graphics so that they feel comfortable.

Task parameter: The initial view of the plane was at an angle that required the maintainers to rotate and zoom to view the necessary components.

Completion of the task was signified by the following:

a. Placing a mark on the 3D graphic to identify all the damaged components. Maintainers should place marks on the graphic wherever marks appeared on the plane. The print screen was used to capture the marker on the 3D graphic.
b. Verbally identify the components that were damaged.

4. Data Collection (gathered during task)

Response times identified when and how often the viewer's features were recorded (i.e., start task, open door 3R, zoom components, pan components, rotate components, remove components, replace components, walk around components, mark damage and complete task)

5. Questionnaire (60 minutes)

Please refer to Appendix D, "Comparative Study Background Information Questionnaire."